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Laser Microfabrication for Silicon Restrictor

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Abstract The restrictor, which is a fluid channel from a reservoir to a chamber inside a thermal micro actuator, has been fabricated using ArF and KrF excimer lasers, Diode-Pumped Solid State Lasers (DPSSL) and femtosecond lasers for a feasibility study. A numerical model of fluid dynamics for the actuator chamber and restrictor is presented. The model includes bubble formation and growth, droplet ejection through nozzle, and dynamics of fluid refill through the restrictor from a reservoir. Since an optimized and well-fabricated restrictor is important for a high frequency actuator, some special beam delivery setups and post processing techniques have been researched and developed. The effects of variations of the restrictor length, diameter, and tapered shapes are simulated and the results are analyzed to determine the optimal design. The numerical results of droplet velocity and volume are compared with the experimental results of a cylindrical-shaped actuator. It is found that the micro actuators having tapered restrictors show better high frequency characteristics than those having a cylindrical shape without any notable decrease of droplet volume. The laser-fabricated restrictors demonstrate initial feasibility for the laser direct ablation technique although more development is required.

Keywords : Thermal micro actuator, Laser microfabrications, Femto-second lasers

1. Introduction

The traditional Micro-Electro-Mechanical-Systems (MEMS) processes such as chemical wet and dry etching using plasma, Chemical Vapor Deposition (CVD), and Physical Vapor Deposition (PVD), etc. are limited to two-dimensional microfabrication. Since they permit three-dimensional fabrication, variety of laser processes for MEMS devices have been researched and developed[1-9)]. The KrF and ArF excimer laser systems have been successfully developed to fabricate complicated structures on polymers[10-12)]. Excimer laser processing of polymer for the nozzles, micro-fluid channels, and chambers of micro actuators and bio-MEMS devices were very successful and applied to mass-production[12)]. Excimer lasers are also one of the best candidates for next generation UV lithography tools[13)]. High performance wafer dicing or curve cutting systems using DPSS lasers and Nd:YAG lasers and water jet combined system were also being developed[8)]. Moreover, the direct ablation (DA) methods for creating three-dimensional structures using DPSS lasers on a silicon wafer were investigated. However, they have some disadvantages such as rough surfaces, micro-cracks, large Heat Affected Zone (HAZ). In an attempt to minimize these effects, some researchers have been studied laser-chemical combined methods, laser microlithography and even more advanced lasers or workstations. Thermal micro actuators, especially inkjet print heads, have being researched and produced widely because they are the most economical device for a high quality color printing[14-16)]. In the actuator, explosive boiling ejects the fluid from inside the chamber through nozzles. This superheat takes place on a thin layer of a heater inside the micro actuator

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*Corresponding Author : [Tel : +82-51-510-2483; E-mail : nano@pusan.ac.kr] chamber[16-17]. The heating makes many small vapor-bubbles on the heater surface and these bubbles grow and form a large, high-pressure bubble (about 64~100 atmospheric pressure inside) that transfers momentum to surrounding fluid and ejects fluid droplets from the chamber[17]. This bubble collapses after the fluid ejection and fluid refills the chamber from a reservoir through the restrictor passage. In this paper, a tapered restrictor passage has been designed to accomplish faster refill for higher frequency operation. Several laser microfabrication techniques have been utilized to fabricate restrictor passages in an effort to overcome the limitations of the traditional MEMS processes for creating three-dimensional geometry. In addition, we will present simulation results that provide insight into the basic designs and functions of the restrictors, micro-channels and reservoir. The numerical results show that a tapered restrictor shape provides better performance than a cylindrical shape. Finally we will compare the numerical results of the actuator which contains cylindrical shaped restrictor with the experimental results.

2. Experimental

2.1. Design for a restrictor

The design of restrictor for thermal actuator has been researched and developed because of its important role in overall actuator performance. It was also proved that the restrictor design was closely related to the frequency of the thermal actuator. Numerical simulation were performed to optimize the shape, length and diameters of the restrictor. A schematic drawing of a cross section of an inkjet printer actuator is shown in Fig. 1. The ink was ejected from the hemispherical chamber "B" through the nozzle opening "A". The ring-shaped resistive heater was located on the upper surface of the chamber and was visible to left and right of the nozzle in the figure. The chamber was replenished with ink from the reservoir (along the bottom of the figure) through the restrictor passage "C". The initial numerical simulations showed that, to implement a micro actuator which ejects 4-30 pico liter (pl) through each nozzle, the restrictor diameter should be in the range of 15-35 μm. The raw material used for the restrictor was silicon. The restrictor length and diameters were determined from the design considerations including heater and chamber sizes and firing performance. To optimize the restrictor design, we must begin with the heater, nozzle and chamber designs. We made numerical models and did parametric studies to determine reasonable fluid velocity, volume, and operating frequency. Since the inlet of the restrictor should be designed for minimal viscous loss, tapered shapes were introduced. During operation, the fluid adjacent to the heater was superheated and ejected through the nozzles, when a short electrical pulse was applied to the thin film resistance heater[15-17]. After firing, the chamber was re-filled through the restrictor which was a micro-fluid channel from the reservoir. A numerical model for the micro actuator was programmed using a Volume of Fluid (VOF) simulation scheme[12]. It was assumed that the initial bubble with 0.1-0.3 μm height was uniformly formed on the heater. The bubble grew from the heater and ejected a fluid

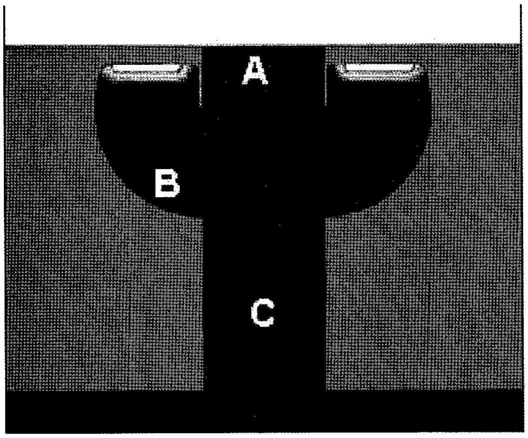

Fig. 1. The nozzle (A) thickness and diameters are 5-10 μm and 15-30 μm, respectively. The restrictor fluid channel (C) connects the chamber (B) to the ink in the reservoir along the bottom-most portion of the diagram.

droplet, after which the bubble collapses and the fluid filled up the chamber again through restrictor[18-19]. Numerous numerical simulations were performed to determine optimal heater, chamber and restrictor designs.

2.2. Laser microfabrication

Laser fabrication of tapered restrictor passages was found to be challenging. When excimer laser radiation irradiates silicon, it is absorbed within a relatively thin surface layer of material and a clean surface expected after the fabrication[12]. For the current work, the excimer laser beam was homogenized and passed through a photomask, reflecting mirrors and a projection lens[12]. The microfabrications of restrictors were tested using 193 nm ArF and 248 nm KrF excimer lasers, q-switched diode-pumped Nd:YAG (DPSS) laser and a femtosecond laser. The cross-sectional views of the nozzles fabricated by the excimer lasers are presented in Fig. 2. Due to the explosive ablation from the silicon material, the finished surfaces inside the tapered holes were not so smooth and the shapes were also distorted. Once the pulsed laser energy is radiated on the silicon wafer, very hot and ionized plasma plume is generated[20]. Although the temperature of this plume varies was the substrate materials, normally its core temperature is increased up to 10,000°K or more. This plasma plume inside the hole is a main factor affecting the melting and flow of silicon. In addition, it was observed that there was a burst near outlet side of the restrictor from the erupted silicon material that extends out into the chamber and adheres to the surface adjacent to the chamber opening. It was also

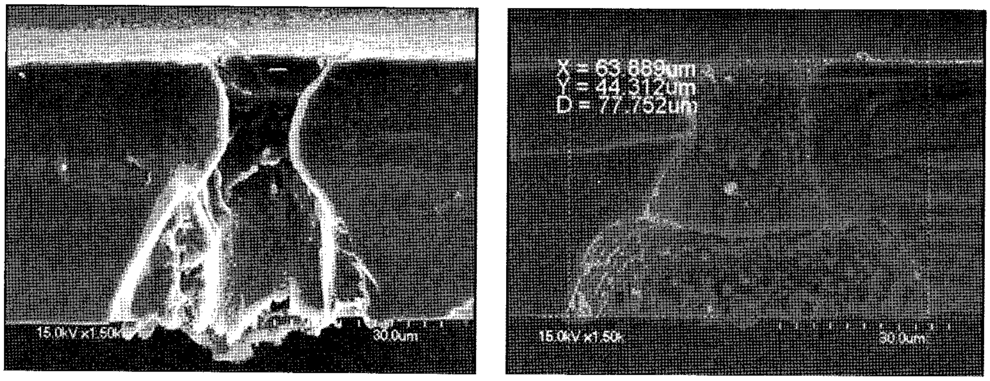

Fig. 2. The SEM photographs of restrictor model *A* (ArF (left) and KrF (right))-thin silicon wafer (about 50 μm thickness).

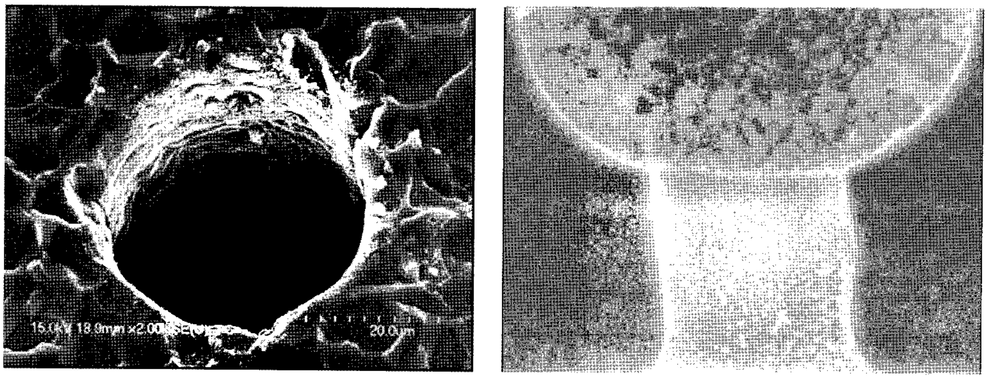

Fig. 3. The SEM photographs of silicon wafer fabrications on an un-polished surface (left) and cross-sectional view of the micro actuator (right). Results of the diode-pumped Nd:YAG (left) and femto-second laser (right). No cleaning process is carried out.

found that there were some recasts adhering near inlet side of the restrictor. These results indicated that there existed a very hot, high pressure region inside the processed holes fabricating using the excimer lasers. If we apply protective layer like polyimide film or coat a thin layer of material such as silicon nitride on both sides of the silicon wafer, the degree of surface contamination due to burst and recast should be reduced. Although the excimer laser could make highly tapered holes easily using photomasks, it was found that the achievement of a clean surface inside the hole was very difficult. In Fig. 3, two SEM photographs of the holes drilled using DPSS laser and femtosecond laser are presented. They are the results before any cleaning process. Since the femtosecond laser produces very short pulses (~150 fs), the recast can be remarkably reduced and the circular shape of the hole can be maintained. The cross-sectional view of the femtosecond laser sample shows a cleaner and smoother surface finish than that of samples produced by the excimer or DPSS lasers. Nevertheless, the direct ablation method for silicon wafer fabrication has its limitation. Since most of the micro actuators are fabricated in a clean room environment, the debris, recast, and erupted materials inside and outside of the drilled holes are not allowed. Some researchers developed a chemical-DA combined method like chlorine-assisted laser microfabrication method which was turned out one of the most effective ways to obtain clean surface condition from silicon wafer7). However, the method required a high-pressure chamber and pumps for chlorine gas environment as well as wafer loading systems into the chamber. Though the four laser types and DA methods were applied for the fabrication of the restrictor, it was found that there was no simple method to fabricate the clean and designed shapes.

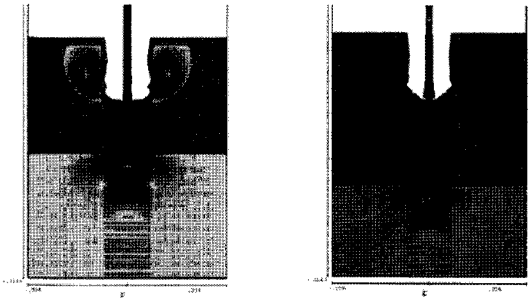

Fig. 4. Fluid flow inside the actuators at the simulation time of 17 μs (left) and 18 μs (right). The nozzle diameters are 28 μm, and restrictor lengths are 30 μm (left) and 40 μm (right).

3. Results

Simulation results are showing the effect of restrictor length changes in Fig. 4. The restrictor length of the left side is 30 μm and that of right side is 40 μm. It was evident that the volume and velocity of the ejected droplet were increased when the restrictor wall friction was increased by making the restrictor opening longer. Droplets from actuators with longer restrictors obtained more thrust from higher chamber pressures associated with higher viscous loss on the restrictor passage wall. However, the flow of ink to refill the chamber from the reservoir also became slower when the restrictor passage was longer when the restrictor was longer. When the restrictor length was 40 μm, the droplet velocity and volume were 7.98 m/s and 12.29 pl, and the computed refill time was 60 μs. If the length of the restrictor was decreased by 10 μm, the droplet velocity and volume became 7.90 m/s and 12.14 pl, and it made the refill time 10 μs (17%) shorter. It was also true that the shorter restrictor made the actuator structure weaker. The effects of the shape variation of the restrictors will be discussed more in the result. The simulation results of the refill time for the three different shaped restrictors are presented at table 1. The original model contains cylindrical restrictor shape and two different shapes-model *A* and *B* are tested. The simulation results that verify the effect of restrictor shapes are presented in Fig. 5. It was found that the tapered restrictor designs allowed faster refill due to less friction near the inlet and through the

Table 1. Comparison of refill time (nozzle diameter is 30 μm and restrictor length is 40 μm)

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

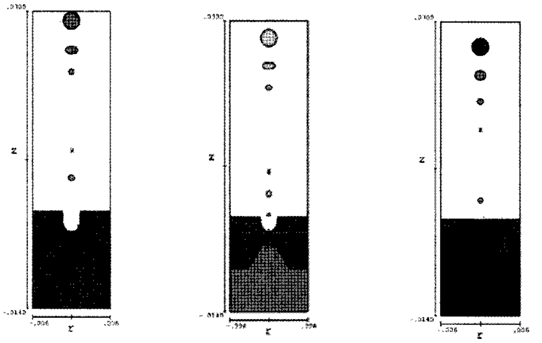

Fig. 5. Refill characteristics of cylindrical model (left) and new restrictor model *A* (middle) and *B* (right) at the simulation time of 33 μs. The taper angle for the new models is 60°. The restrictor lengths of the model *A* and *B* are 10 μm and 0 μm, respectively.

restrictor from the simulation. The results showed that, at 33 s, the refill of the cylindrical model was in progress while that of the restrictor model A was partially completed and restrictor model B was totally refilled. Model B has a larger diameter opening into the chamber than does model A and the entire restrictor channel was tapered. The refill time was reduced to almost 50% using the model *B*, but the droplet volume and velocity are almost same as model A. Comparing only the droplet volumes, the model *A* (cylindrical + model *B*) was slightly better than the model *B*. These results clearly showed that the tapered restrictor had better refill characteristics. It was obvious that the faster refill time, the higher the maximum operating frequency is. When the restrictor length was increased, the droplet volume and velocity were slightly increased while the refill frequency was decreased. If the restrictor length became longer, the corresponding resistance, wall friction, inside the restrictor was increased. It meant that the firing droplet was obtained more thrust from the backside. Therefore the velocity and volume were increased. On the other hand, the resistance prevented the refill of fluid causing the low frequency characteristics. The affects of the diameter variations were inverted from those of the length variation since the viscous resistance was decreased when the restrictor diameter was increased. The actuator which contains 20 μm nozzle diameter and 25 μm restrictor length was fabricated for the verification of the simulations. Since the method for the tapered restrictor was in pursuit, the cylindrical restrictor shape was fabricated using an established dry etching method. A 15 V voltage input was applied to the actuator for 0.4 μs. The photographs of the fluid ejection from the actuator are presented

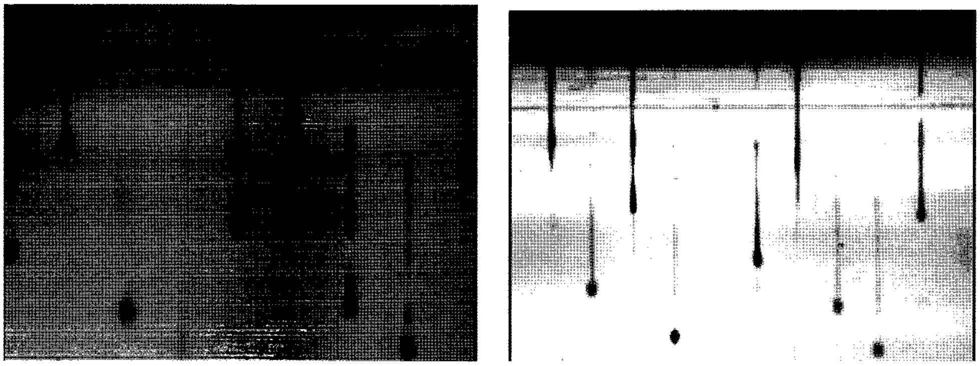

Fig. 6. Comparison of ejection characteristics of the cylindrical restrictor at the operating frequencies of 15 KHz (left) and 18 KHz (right).

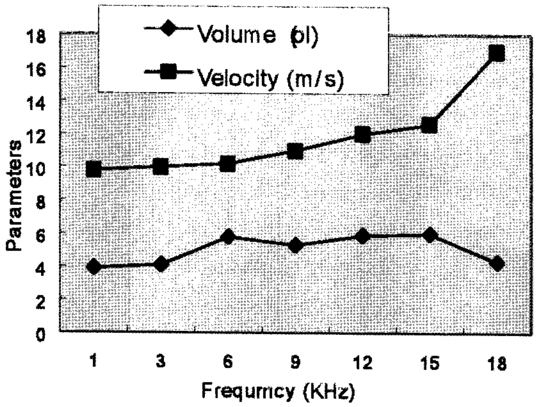

Fig. 7. Experimental result showing droplet mass (pl) and velocity (m/s) for a cylindrical restrictor.

in the Fig. 6. They are the results at the operating condition of 15 and 18 KHz. The left side photograph shows very "normal" behavior at the operating frequency of 15 KHz. The droplet behavior at the 3 KHz higher frequencies is presented in the right side. The shape of droplet does not look normal. The ejection behavior begins to transit into the "spear" shape due to poor refill characteristic. The normal ejection at the high frequency means higher performance. The experimental result of volume and velocity changes according to the operating frequencies is shown in Fig. 7. The droplet velocity and volume are 9.9±1.0 m/s and 5.9 ±0.5 pl at the operating frequency of 6 KHz. The experimental results have error limits of ±1.0 m/s for the velocity and ±0.5 pl for the volume. Comparing the experimental results with the simulation results of 8.56 m/s and 4.61 pl, the velocity was relatively well matched but the computed volume was smaller than the experimental results. This higher experimental volume was caused by the coupled thermal and fluid behavior of the real actuator. As described in the introduction, the thermal actuator was operated at the very high temperature and pressure. This continuous heat from the thin film heater into the surrounding fluids made fluid viscosity smaller. The viscosity was one of the very important factors that determined the droplet velocity. One of the most advanced commercial Computational Fluid Dynamics (CFD) package using VOF scheme which was the standard way to simulate free boundary microfluidics, Flow-3D, did not support the fluid/thermal coupled problem at this time. Consequently, it was very difficult to simulate thermal actuator problem including coupled flow accurately. Since the simulation could not consider any viscosity changes due to the increase of the fluid temperature, it was expected that the volume of real fluid was somewhat more than we simulated.

4. Conclusions

A numerical model of fluid dynamics for the actuator chamber and restrictor was presented. The model included bubble formation and growth, droplet ejection through nozzle, and dynamics of fluid refill through the restrictor from a reservoir. The effects of variations of the restrictor length, diameter, and tapered shapes were simulated and the results were analyzed to determine the optimal design. The numerical results of droplet velocity and volume were compared with the experimental results of a cylindrical-shaped actuator. It was found that the micro actuators having tapered restrictors showed better high frequency characteristics than those having a cylindrical shape without any notable decrease of droplet volume. Although the laser microfabrication was an established technology for the micro actuator prototyping, the DA methods were very difficult to apply for the fabrication of very delicate MEMS device. As future work, more theoretical and numerical investigations for the fluid/thermal coupled problem will be performed to determine more accurate and optimal designs for the complicated restrictors and the chemical-DA combined method and more femtosecond laser experiments will also be tested for better surface and shape conditions.

Acknowledgements

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