Design and Fabrication of Electrostatic Inkjet Head using Silicon Micromachining Technology

Youngmin Kim*, Sanguk Son*, Jaeyong Choi*, Doyoung Byun, and Sukhan Lee***

***Abstract*—This paper presents design and fabrication of optimized geometry structure of electrostatic inkjet head. In order to verify effect of geometry shape, we simulate electric field intensity according to the head structure. The electric field strength increases linearly with increasing height of the micro nozzle. As the nozzle diameter decreases, the electric field along the periphery of the meniscus can be more concentrated. We design and fabricate the electrostatic inkjet heads, hole type and pole type, with optimized structure. It was fabricated using thick-thermal oxidation and silicon micromachining technique such as the deep reactive ion etching (DRIE) and chemical wet etching process. It is verified experimentally that the use of the MEMS inkjet head allows a stable and sustainable micro-dripping mode of droplet ejection. A stable micro dripping mode of ejection is observed under the voltages 2.5 kV and droplet diameter is 10 µm.**

***Index Terms*—MEMS technology, silicon deep etching, electrostatic inkjet head, electrostatic ejection, silicon micro nozzle**

I. INTRODUCTION

New advancements in the design and manufacturing process of industrial inkjet head for micro printing are significantly changing the application area of the inkjet printing technology [1-3]. Ink-jet printing technique is very attractive for forming micro-size patterns for flat panel displays (FPDS), printing circuit board (PCB), semiconductor, biological, optical, and sensor devices due to its low temperature process, direct writing, and rapid photolithography process [4,5].

The inkjet printing mechanisms has been used thermal bubble, piezoelectric and electrostatic method. Thermal and .piezoelectric inkjet printing are based on pushing out the liquid in a chamber through a nozzle by actuators, such as thermal bubble and piezoelectric actuators. However, thermal bubble actuator has the heat problem when the array of nozzle make in a large area and piezoelectric actuator is difficult to make droplet smaller than nozzle size [5]. Also, the head consisting of piezoelectric or a heater element has the disadvantage of the complex structure. Electrostatic inkjet are based on protruding through an orifice induced by an electric field forms a meniscus called the Taylor cone [6] and can separate from the meniscus tip as fine droplets much smaller than the orifice diameter. Electrostatic inkjet has a greater advantage than piezoelectric inkjet and thermal inkjet in the ability to eject fine droplets and in the simplicity of structure [7]. Lee et al. [8-9] have been proposing and developing an electrostatic drop-on-demand print head that is capable of overcoming the limitations of piezoelectric and thermal bubble print heads described above. Several researchers studied the electrostatic micro-dripping mode for industrial application. Hiroyuki et al. [10] investigated electrostatic ink jet phenomena in pin-to-plate discharge system. Yuji Ishida et al. [11] demonstrated ink-droplet formation in double-gate electro-spray. The droplet ejection using a needle-type inkjet head was also investigated.

In this paper, we present the analysis and fabrication of the electrostatic inkjet head using the microelectromechanical system (MEMS) technology. First, a micro droplet is

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formed from the liquid meniscus due to the induced electric field. The electric field is obtained by solving the Maxwell governing equation. Using the parametric study, we find the optimal shape of the nozzle geometry in a view of enhancing and focusing the electric field near the center of meniscus. Then, the electrostatic inkjet head was fabricated by the thick-oxidation process and the MEMS technology. Finally, the characteristic of drop-on-demand ejection is analyzed using the electrostatic inkjet method and MEMS structure of the nozzle.

II. DESIGN AND SIMULATION

To achieve an effective micro dripping ejection, inkjet head was designed and fabricated to provide concentrated electric force on nozzle and pole tip. Fig. 1 and Fig. 2 show the schematic of the proposed electrostatic inkjet heads of hole type (Fig. 1) and pole type (Fig. 2). This structure consists of reservoir, nozzle and conductive pole to concentrate electric field.

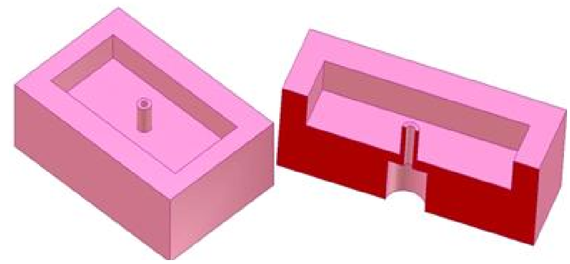
Micro droplet is formed from the liquid meniscus due the induced electric field. The electric field is obtained by solving the following governing equations.

$$\nabla \cdot \varepsilon \nabla \varphi = -\rho \quad (1)$$

$$\vec{E} = -\nabla \varphi \quad (2)$$

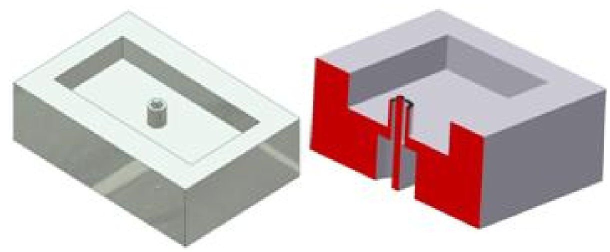
where $\vec{E}$, φ, ε, and ρ are the electric field vector, the electric potential, the permittivity, and the charge density, respectively. These equations are solved by FEM (finite element method).

Fig. 3 shows the schematic of the proposed electrostatic inkjet head. This structure consists of glass electrode part and nozzle part with a reservoir. The inkjet head utilizes electrostatic forces that act between electrode and nozzle tip. The electrostatic forces are created when a voltage is applied electrode and head bottom. The surface of the inkjet head becomes wet with liquid after applying an electric field. Then charged liquid is separated from the inkjet head tip as fine droplets. When the force induced by an electric field on the inkjet head tip is stronger than the resultant force of surface tension, ink viscosity and conductivity, the meniscus called Taylor cone is generated and fine droplets is separated from the head by Coulomb force.



(a) Top view (b) Cross sectional view

Fig. 1. Schematic of the nozzle part of the proposed hole type electrostatic inkjet head.



(a) Top view (b) Cross sectional view

Fig. 2. Schematic of the nozzle part of the proposed pole type electrostatic inkjet head.

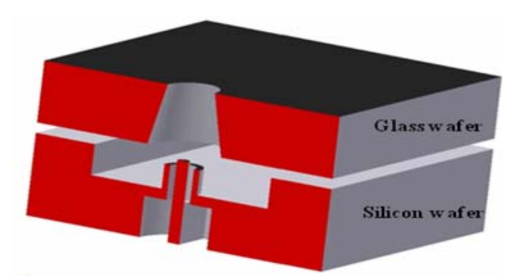


Fig. 3. The structure of the proposed pole type electrostatic inkjet head.

Fig. 4 shows the result of the electric field simulation used the DI water as the liquid solution. Fig. 5 shows the electric field strength as a function of the variation of the nozzle height. The electric field strength increases linearly with increasing height of the micro nozzle. Also, as the height of the nozzle increares, the electric field along the periphery of the meniscus can be more concentrated.

In order to find optimal structure and demonstrate concentration of electrostatic force at the pole edge, we have simulated pole type inkjet head using FEMLAB. Fig. 6 shows the result of the electric field simulation used the DI water as the liquid solution. The structure of the nozzle inner diameter, thickness, and pole diameter are 80 μm, 20 μm and 40 μm, respectively. The pole hight is 50 μm. As the result, the concentration of electrostatic force was showen at the conductive pole edge.

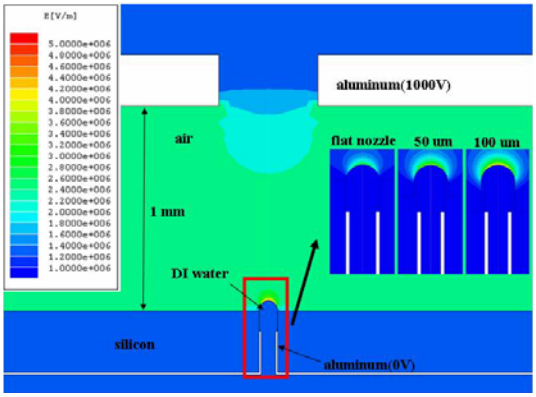


Fig. 4. Electric field simulation of the hole type inkjet head.

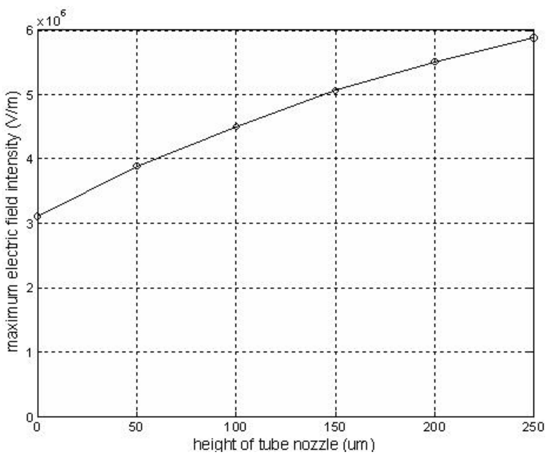


Fig. 5. Electric field strength as a function of the nozzle height of the hole type inkjet head.

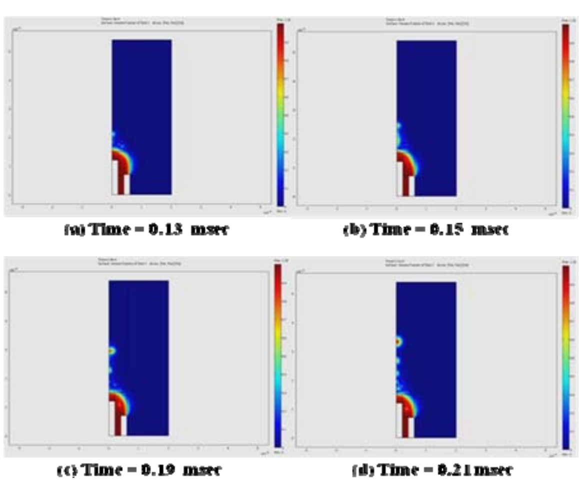


Fig. 6. Electric field simulation as a function of the time varitation of the pole type inkjet head.

III. Fabrication

The proposed electrostatic inkjet head is consists of the glass top-layer part and the silicon bottom-layer part. They are fabricated using thick-thermal oxidation and silicon micromachining technique such as the deep reactive ion etching (DRIE), separately. The top electrode was previously fabricated on glass wafer. The aluminum layer is deposited by sputter on the glass wafer, and then dry film is coated by laminator and patterned the hole of the ink ejection. The electrode of the hole type is formed using the sand blaster.

The fabrication process of the electrostatic inkjet head with the micro nozzle is shown in Fig. 7. The p-type, (100)-oriented double-side silicon wafer substrate is used. First, a thick silicon oxide of 2 μm is thermally grown (Fig. 7(a)). This silicon oxide layer is used as a mask for forming the nozzle and backside reservoir. The front side is patterned by photolithography using the thick positive photoresist. The pole and nozzle for inkjet ejection are formed by oxide dry etching and DRIE (Fig. 7(b)). The depth of the nozzle outer part is about 70 μm. Next, the back side oxide is patterned by photolithography and dry etching (Fig. 7(c)). The reservoir for ink storage is then formed using DRIE (Fig. 7(d)). To penetrate wafer of patterned nozzle, the front side silicon is etched using DRIE (Fig. 7(e)). Finally, the oxide layer of the wafer is etched by the chemical wet etching included HF solution and cleaned before the next process (Fig. 7(e)).

Fig. 8 shows photomicrograph of the nozzle part of electrostatic inkjet head after silicon deep etching. The depth of nozzle outer part is 50 μm. Fig.9 shows photomicrograph of the nozzle part of electrostatic inkjet head inserted the pole. Fabricated head's nozzle inner

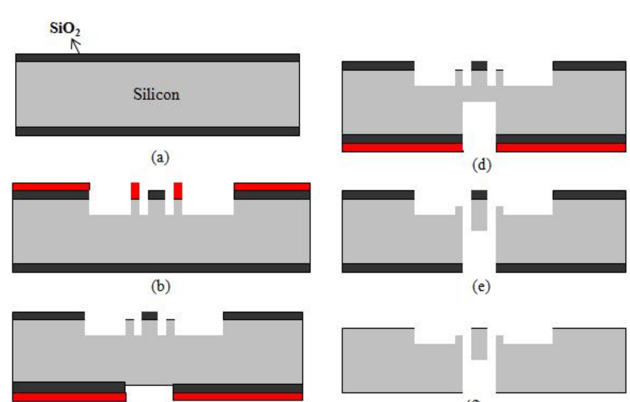


Fig. 7. Fabrication Process : (a) SiO_2 layer on silicon wafer, (b) Oxide(deep Si etch mask) patterning and deep Si etching, (c) reservoir patterning on the bottom silicon wafer, (d) Deep Si etching, (e) Deep Si etching for pole formation, (f) SiO_2 removal by the HF solution.

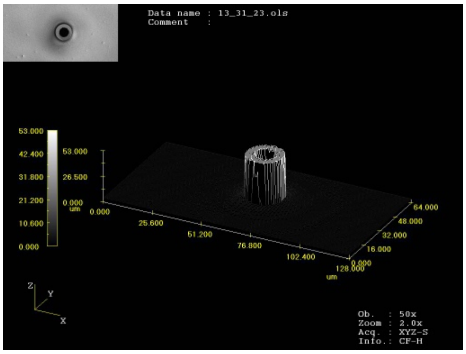
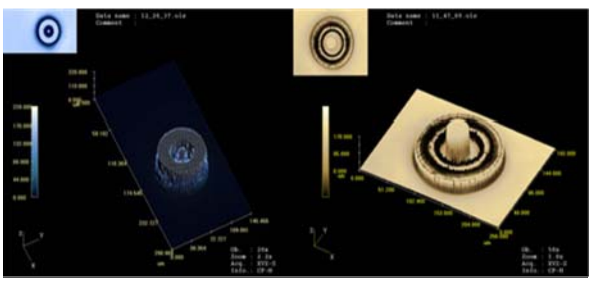


Fig. 8. Photomicrograph of the nozzle part of hole type electrostatic inkjet head after silicon deep etching process.



(a) (b)

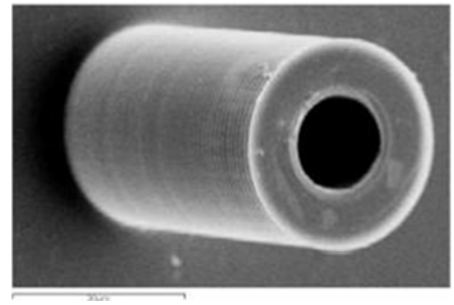
Fig. 9. Photomicrograph of the nozzle part of pole type electrostatic inkjet head, (a) after first, (b) 2nd silicon deep etching process.

diameter, thickness, and pole diameter are 60 µm, 20 µm and 20 µm, respectively. The depth of nozzle outer part is 70 µm. To obtain opened pole, we have performed DRIE process. The etch rate ratio of the etched nozzle has 1 : 1.5. Fig. 9(b) shows photomicrograph of the nozzle part of electrostatic inkjet head after DRIE process of the Fig. 7(e). We measure the fabricated pole using the 3D photomicroscope (LEXT, OLYMPUS Co.) equipment.

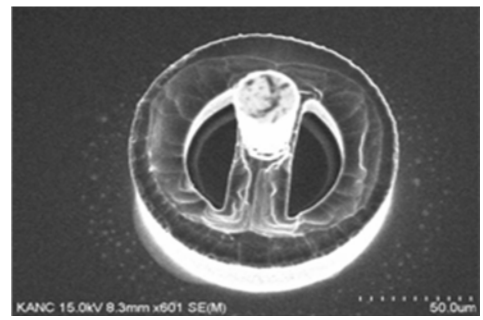
Fig. 10 shows the SEM images of the nozzle part of the electrostatic inkjet head after the fabrication process. Fig. 10(a) shows the hole type nozzle fabricated MEMS technology. The inner diameter and outer diameter of the fabricated nozzle are 20 µm and 50 µm, respectively. Fig. 10(b) shows the pole type nozzle opened conductive pole of 50 µm to provide concentrated electric force on pole tip. The height of nozzle outer part and pole diameter are 120 µm and 20 µm, respectively.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 11 shows the schematic of the experimental system for electrostatic inkjet ejection. This system consists of the head system, the high speed camera, micro syringe pump, power, and computer.



(a)



(b)

Fig. 10. SEM images of the nozzle part, (a) of hole type (b) of pole type electrostatic inkjet head.

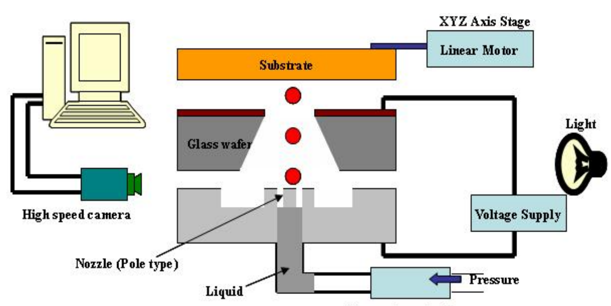


Fig. 11. The schematic of the experimental system.

A high speed camera (IDT XS-4) with a micro-zoom lens and a halogen lamp was used to visualize droplet ejection. The high speed camera can image 5000 frames per second at a 512 x 512 resolution with a micro-zoom lens and a LED light source were used. A high voltage power supply (maximum voltage of 3.0 kV) was used with a relay switch to control electrostatic field. The liquid have been supplied to the nozzle with constant velocity by micro syringe pump and the voltage has been provided to the upper electrode.

The jetting mode depends on the applied voltage, the flow rate, and the liquid properties, such as electric conductivity, surface tension, and viscosity. To make an experiment on the micro ejection of the electrostatic inkjet head, the conductive liquid of the mixture of D2O, SDS, and micelle-suspended Carbon Nano Tube (5 %wt SWNT) solution is used as ink. The outer diameter of the nozzle is 50 μm and the gap between the upper electrode and the nozzle orifice is set about 800 μm. The constant flow rate by a micro pump is kept at 0.1 μl/min.

Fig. 12 shows the series of image frames observed with the high-speed camera showing the micro droplet ejection by the fabricated hole type inkjet head. The supplied voltage is kept at 1.7 kV between the upper Al electrode and the nozzle ground. The droplet diameter ejected from the nozzle tip is measured about 80 μm.

Fig. 13 shows the series of image frames observed with the high-speed camera showing the micro droplet ejection by the fabricated hole type inkjet head. The supplied voltage is kept at 2.5 kV. The droplet diameter ejected from the nozzle tip is measured about 10 μm. Also, a stable micro dripping mode or Cone-jet mode of ejection is observed under the voltages ranged from 1.9 kV to 2.4 kV. These results show that the micro dripping mode of tiny droplet size is observed by experimental system. And, the ejection experiment of the conductive ink using the pole type electrastatic inkjet head is in progress.

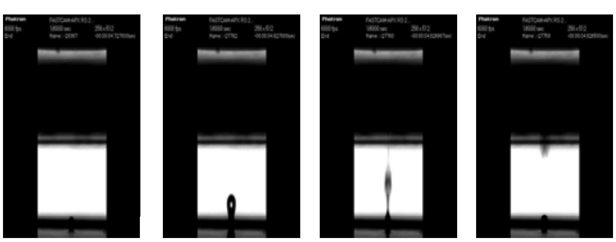


Fig. 12. Images taken with high-speed camera showing event of micro ejection from nozzle of inkjet head.

Fig. 13. Images taken with high-speed camera showing event of micro ejection from nozzle of inkjet head.

V. CONCLUSIONS

The hole type electrostatic inkjet head and pole type electrostatic inkjet head with conductive pole inserted in a silicon nozzle have fabricated using thick-thermal oxidation and silicon micromachining technology. To form silicon nozzle and conductive pole in the silicon nozzle, we used DRIE process.

As a result of pole type inkjet head, Fabricated head's nozzle inner diameter, thickness, and pole diameter are 60 μm, 20 μm and 20 μm, respectively. The height of nozzle outer part and pole diameter are 120 μm and 20 μm, respectively. The height of the conductive pole is about 50 μm. Also, The inner diameter and outer diameter of fabricated hole type nozzle are 20 μm and 50 μm, respectively.

The fabrication process used in this paper was very simple and reproducible. It is expected that this fabrication process can apply for inkjet head of fine pitch and multi-array.

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