A HIGH RESOLUTION, ELECTROSTATICALLY-DRIVEN COMMERCIAL INKJET HEAD

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ABSTRACT

A fully-micromachined, low power, large nozzle count and high resolution "electrostatically actuated inkjet (SEAJet^{TM})" head has been developed for a POS printer. As 3D multiple-step structured nozzles are required for straight and high frequency ink ejection, it was formed by ICP deep-RIE employing a "multiple-step mask method" which makes troublesome stereo-photolithography unnecessary and 128 nozzles/chip were fabricated simultaneously. The required thin, 2 μm-thick pressure plates were formed by B doped etch-stop technology combined with two-step alkaline etching which enables smooth-surfaced and uniform (2.15+/-0.35 (3 σ) μm) pressure plates.

The typical driving voltage is 26.5V and the SEAJet head has achieved the uniform ink ejection up to a driving frequency of 18kHz. The life of the actuator has been confirmed to be more than 4 billion times actuation. The typical printing speed of the POS printer is 15 l/s (lines per second) for a rolled paper and 3ppm (papers per min.) for A4 paper in 360dpi (dots per inch) high resolution, a performance level that makes this the fastest inkjet POS printer in the world. The average power consumption was measured as only 0.525mW/nozzle. It is only one-thousandth of that of a typical thermal inkjet.

INTRODUCTION

We have proposed a SEAJet^{TM} (Static Electricity Actuated inkJet,) which is a novel inkjet head driven by on-demand electrostatic force[1]. It has several advantages such as low power consumption, small size and high mass productivity compared to the conventional, thermal or piezo electric inkjet heads. The first generation SEAJet has a rather small number of nozzles in low density because it was designed for an electric calculator printer. In order to adopt SEAJet in a wider application range, we have developed a high resolution, large nozzle count, new generation SEAJet and it was installed in a POS printer as shown in Fig.1.

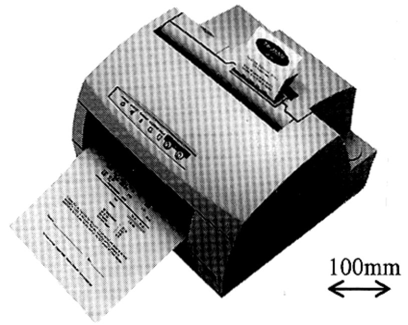

Fig.1: Appearance of the EPSON "TM-J8000" POS printer

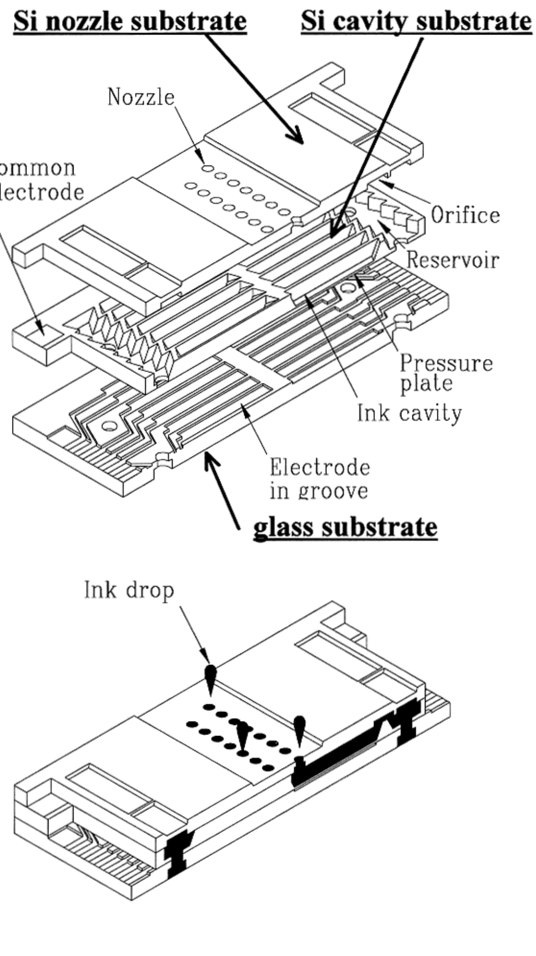

Fig.2: Schematic diagram of a high resolution SEAJet

The high resolution SEAJet head also has a three-layer structure as shown in Fig.2. In order to increase the nozzle density to the overall nozzle pitch of 14nozzles/mm (corresponds to 360dpi), we selected a "face eject" structure for the high resolution SEAJet. High precision structures such as nozzles, walls and pressure plates, which were required for the high resolution SEAJet, demanded several new micromachining processes as follows.
Today, ICP deep-RIE is widely used in MEMS applications[2]. We selected this technology for the SEAJet nozzle fabrication early in its development because it seemed most suitable for etching the high precision, straight holes with the diameters of several tens of μ m. Also, the "multiple-step mask method" is simple and suitable for the fabrication of high precision three-dimensional (3D) MEMS structures[3]. We realized the 3D structured nozzles (diameters: ϕ28+/-2 μ m) by the simplest method which utilizes only thermal SiO_2 as an etch mask[4].
According to the design considerations described below, we concluded that a thin, 2 μ m-thick pressure plate (in the case of Si) was required for the typical driving voltage of 26.5V. There are various kind of methods for fabricating a thin "pressure plate", such as boron (B) doped etch-stop, surface micromachining, SOI and so on. In the case of SEAJet, the B doped etch-stop method seemed the best and cheapest method because single crystal Si is favorable as a vibrating material and the high density ink cavity and thin pressure plate can be formed simultaneously in a (110) Si substrate.
The ink ejection mechanism operates as follows: an electrostatic actuator generates pressure which effects the on-demand ink drop ejection as explained in Fig.3.
The design considerations, fabrication processes and characterizations of the new generation SEAJet are described in this paper.

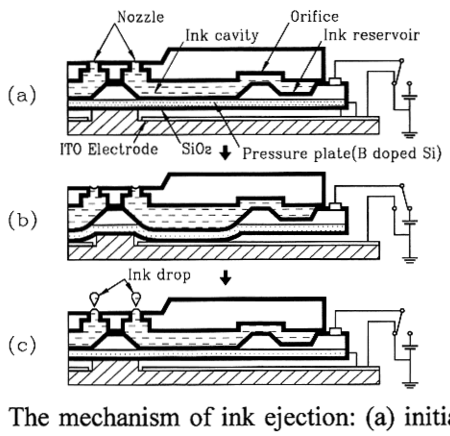

Fig.3: The mechanism of ink ejection: (a) initial state, (b) DC voltage is applied between the pressure plate and the electrode, (c) DC voltage is reduced to 0 and an ink drop is ejected

DESIGN CONSIDERATIONS FOR THE HIGH RESOLUTION SEAJet

Inkjet POS printers are developed and designed for use in retail operations such as hotels, exclusive restaurants, coffee houses, bookstores and pharmacies. Requirements for an inkjet POS printer are as follows:

1) High printing quality (such as for bar code)
2) High speed printing(high throughput)
3) Small size
4) Low power consumption
5) Long life and durability under heavy duty usage
6) Low acoustic noise
7) Plain paper printing versatility

The high resolution SEAJet head was also developed and designed to satisfy these requirements. To realize the high print quality of 360dpi, we designed the SEAJet head to have a 180dpi×2column, face eject nozzle configuration. For high speed printing, we created a 128 multi-nozzle head, designed to enable a maximum driving frequency f_d of more than 16kHz.
As the first step of the design, the main specifications of the high resolution SEAJet head were determined as follows:

Typical driving voltage V: 26.5 (V)
Driving (ejecting) frequency f_d: $\leqq$ 16 (kHz)
Nozzle pitch p: 141.2 (μ m)
Ink drop weight w: 22.5 (ng/drop)
Ink drop velocity v: 6.5 (m/sec) +/-20%
Deviation of ejecting direction : $\leqq 1°$

The ink path way and the actuator of the high resolution SEAJet are designed to satisfy the above specifications by solving acoustic equations of motion for the SEAJet head[1]. We have adopted the following values:

$$M = 4.4\times10^{8}\,(kg/m^{4}),\quad R = 12.0\times10^{12}\,(N\cdot s/m^{5})$$
$$C = 2.1\times10^{-19}\,(m^{5}/N),\quad \Delta Q = 40\,(pl)$$

where M is the acoustic mass of the overall ink path way, R is the acoustic resistance of the overall ink path way, C is the acoustic capacitance of the pressure plate and ΔQ is the displacement of the actuator.
Based on the fabrication process capacity and past data, the dimensions of both ink path way and actuator were fixed and designed to satisfy these parameters. The main dimensions of these are as follows:

Pressure plate length L : 2.853(mm)
Pressure plate width W : 108(μ m)
Pressure plate thickness T : 2.15+/-0.35(μ m)

Air gap length g : 0.18+/-0.018 (μ m)
Nozzle diameter Dn : ϕ 28+/-2 (μ m)
Nozzle length Ln : 25 (μ m)

where g and T are fixed to enable the generation of enough pressure for ejecting an ink drop under driving voltage V. W is also derived from the nozzle configuration. L is fixed according to the displacement of the actuator ΔQ.
The diameter of nozzle Dn is determined to satisfy ink drop velocity v. In order to keep the frequency characteristics of v and w flat in the high frequency band, i.e. up to 18kHz, the nozzle length Ln is designed to be shorter than the value of $w/(\pi Dn^2/2)$.
Furthermore, in order to control ink flow direction in the ink pass way near the nozzle, we designed a "throat" that is connected to the nozzle. It also can control the deviation of an ink drop's ejecting direction. The diameter of the throat is designed to be larger than Dn and dimensions for the throat are fixed experimentally as follows:

Throat diameter Dn2: ϕ 66 (μ m)
Throat length Ln2: ϕ 55$\pm$7 (μ m)
Discrepancy of each center position between nozzle and throat: $\leqq$ 5 (μ m)

FABRICATION PROCESS

The high resolution SEAJet consists of the nozzle substrate, the cavity substrate and the glass substrate as shown in Fig.2. Each substrate was fabricated by a micromachining process and then bonded to each other and finally diced into chips. The micromachining processes for each substrate are described below.

Nozzle Substrate Fabrication Process

Several methods have been tried to fabricate 3D structures in bulk MEMS. Stereo-photolithography applying spray-coating resist or electrodepositing resist[5] on the 3D shaped surface is generally difficult and complicated. Moreover, electrodepositing resist has a disadvantage in that it cannot be coated on non-conductive surfaces. The multiple-step mask method[3] is a solution for the above-mentioned issue. In this method, the etch mask is processed to have patterns corresponding to the required 3D structures in advance while the surface is almost plain. In our process, "monolithic" thermal SiO_2 was used as a multiple-step mask[4].
First, a 180 μ m-thick (100) Si substrate was wet oxidized to have a 1.35 μ m-thick SiO_2 and then the back-side thermal oxide was selectively etched to have multiple-step, concentric nozzle patterns by using a half etching as shown in Fig.4(a). The thickness of the thermal oxide corresponding to the throat was adjusted to 0.5 μ m. Subsequently, the first deep-RIE was performed in an STS Multiplex ICP system. A cross-sectional SEM photograph of the state is shown in Fig.5(a) and the depth of the etched hole was controlled to be deeper than 55 μ m. The thickness of the thermal oxide corresponding to the throat became as thin as about 0.2 μ m during the first deep-RIE. The substrate was soaked into HF based etchant and the above-mentioned thermal oxide was fully removed (The other part of the oxide still remained and the thickness became about 0.7 μ m). Next, the second deep-RIE was performed to create the holes corresponding to the nozzles and throats simultaneously as shown in Fig4(c) and a cross-sectional SEM photograph of the state is shown in Fig.5(b). The depth of the hole corresponding to the throat was 55+/-7 μ m while that of the nozzle became approximately 35 μ m, shallower than the state after the first deep-RIE. This occurred due to micro-loading effect. As a consequence, the desired 3D multiple-step structure was constructed using the multiple-step mask method. After the second deep-RIE, the remainder of the SiO_2 etch mask was fully etched away, the substrate was wet oxidized again and the thermal oxide of the front side was patterned as shown in Fig.4(d). Then time-controlled anisotropic potassium hydroxide (KOH) etching was performed as shown in Fig4(e). Consequently, the nozzles were opened and their length became 25+8/-9 μ m. Finally, the substrate was wet oxidized to have a protective thermal oxide as shown in Fig4(f).

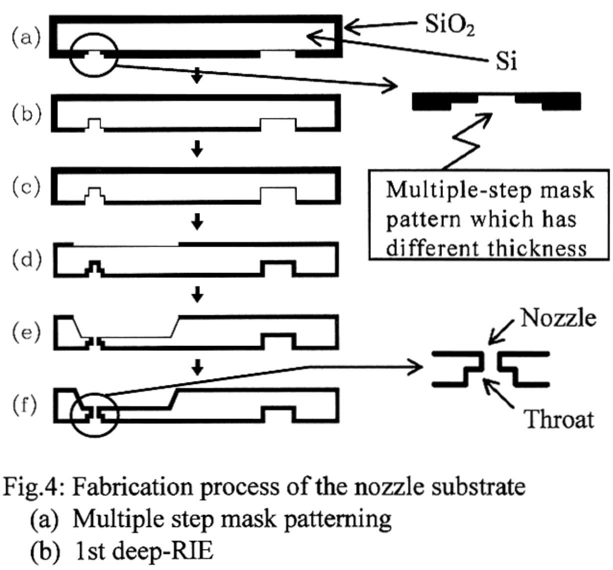

Fig.4: Fabrication process of the nozzle substrate
(a) Multiple step mask patterning
(b) 1st deep-RIE
(c) 2nd deep-RIE
(d) Thermal oxidation and patterning
(e) Wet anisotropic etching
(f) Final thermal oxidation

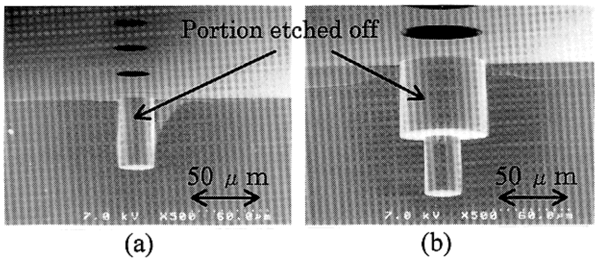

Fig.5: Cross-sectional SEM photographs of a nozzle (a) after 1st deep-RIE and (b) after 2nd deep-RIE

Cavity Substrate Fabrication Process

The etch rate of Si in an alkaline solution decreases when the B concentration in Si becomes higher[6]. A KOH aqueous solution was selected as an etchant because it enables the higher aspect-ratio structures in (110)Si substrate[7]. B was doped into a Si surface using a solid B source (BoronPlus, TECHNEGLAS Inc.) and the diffusion condition was determined as 6 hours in N_2-0.5%O_2 at 1100℃. The B concentration profile was observed as shown in Fig.6. The B profile curve after wet oxidation reached a peak concentration of approximately 9×10^{19} atms/cm^3 at the depth of approximately 2 μ m. Then, we tried the wet anisotropic etching using 10 weight%KOH aq. which was expected to show a relatively high etch-stop ability. The etching was done for 105min at 80℃. 2 μ m-thick pressure plates were produced, however, they exhibited poor thickness uniformity, i.e. 2.1+/-0.9 μ m, which did not satisfy the desired thickness accuracy. This meant the selectivity at 10%KOH was not acceptable. Additionally, it showed a relatively large surface roughness Rt of approximately 0.5 μ m as shown in Fig.7, which was taken by a surface profiler (P11, KLA-Tencor Corporation).
Then, we investigated the etch selectivity(ratio between the etch rate in non-doped Si and the minimum etch rate in B doped Si) and the roughness of the etched surface in a wide range of KOH concentrations as shown in Fig.8 and Fig.9 respectively. Consequently, we concluded that lower concentration KOH aq., especially lower than 3%, gave us higher selectivity but it produced non-negligible roughness on the etched surface.

two-step etching process

Finally, we came to the idea of a "two-step etching" process: perform the first etching in relatively high concentration KOH solution to keep surface roughness as low as possible, and the second etching in relatively low concentration KOH to get higher selectivity. The fabrication process flow of the cavity substrate applying two-step etching is shown in Fig.10. The back side of the 180 μ m-thick, p type(dopant:B,8-12 Ωcm), double-side polished, (110) oriented Si substrate was B doped heavily by the above-mentioned procedure and

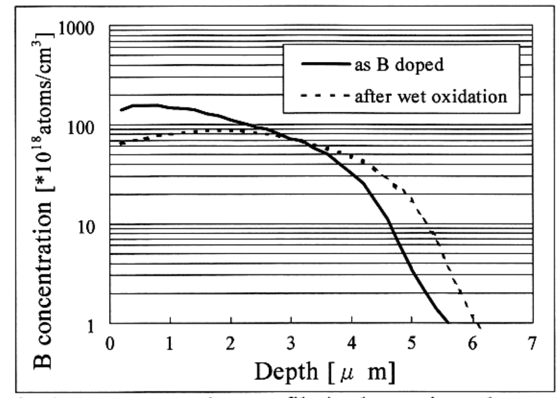

Fig.6: B concentration profile in the cavity substrate

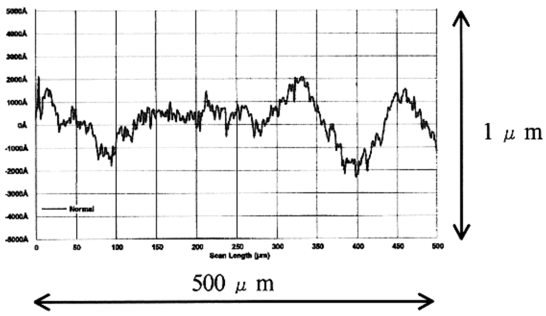

Fig.7: The surface roughness of the pressure plate etched in 10%KOH

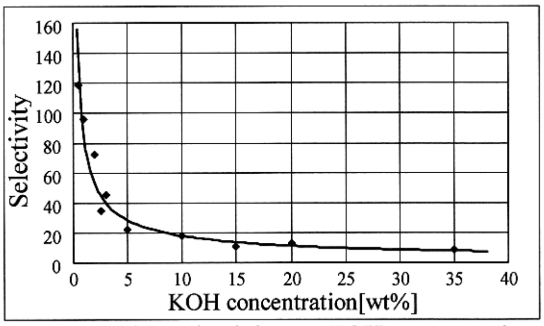

Fig.8: Etching selectivity vs. KOH concentration

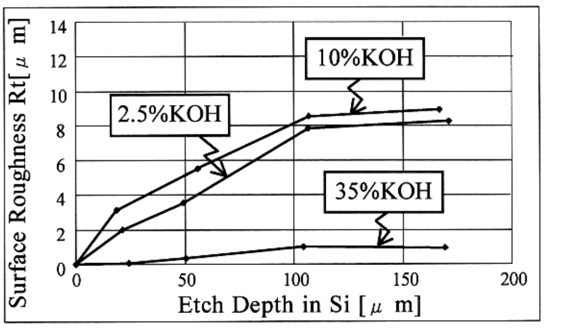

Fig.9: Surface roughness vs. Etch depth for various KOH concentrations

then wet oxidized for 2 hours at 1080℃ to form 1.2 μ m-thick oxide as shown in Fig.10(a). Then, the front-side thermal oxide was multiple-step patterned corresponding to the ink cavity and ink reservoir as shown in Fig.10(b). The target width of the ink cavity is 100 μm and that of the wall is 40 μm. The first KOH etching was performed using 35 weight%KOH aq. at 80℃ to get the etch depth of 170 μm. The surface state at that point is shown in Fig.11(a). The surface roughness Rt was approximately 0.8 μm. Subsequently, low concentrate second etching was done in 2.5 weight%KOH. Etch stop phenomenon occurred and then the etching process was stopped. The surface state at that point is shown in Fig.11(b). The surface was smooth and the roughness Rt was smaller than approximately 0.2 μm.

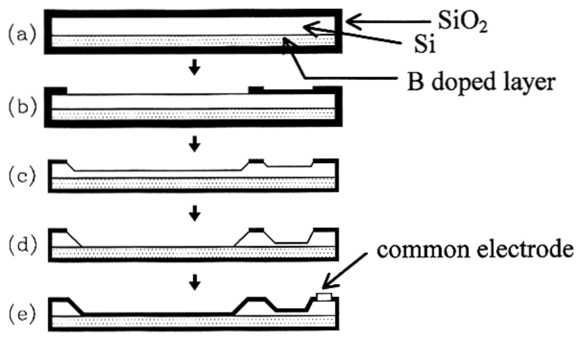

Fig.10: Fabrication process of the cavity substrate
(a) Boron diffusion and thermal oxidation
(b) Multiple-step mask patterning
(c) 1st KOH wet anisotropic etching
(d) 2nd KOH wet anisotropic etching
(e) Final thermal oxidation and common electrode formation

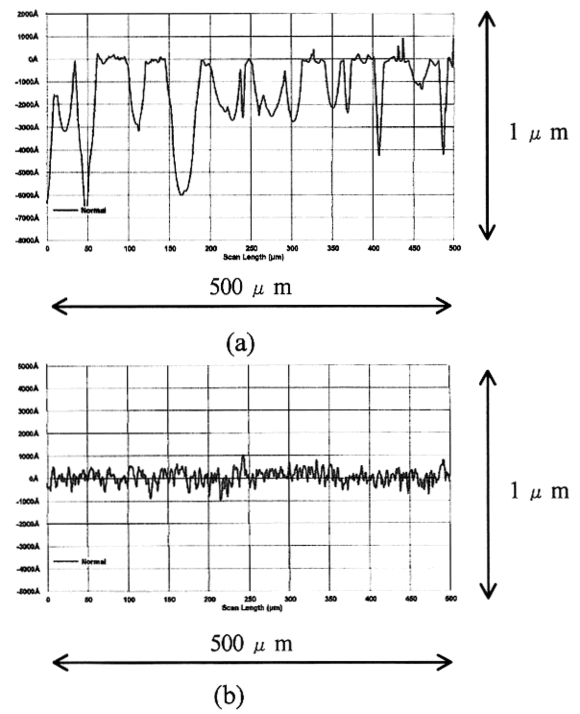

Fig.11: Roughness of the etched surface after (a) 1st, 35%KOH etching and (b) 2nd, 2.5%KOH etching

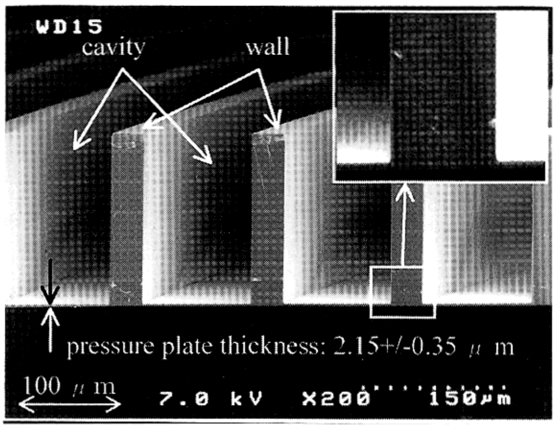

Fig.12: A cross-sectional SEM photograph of the cavity substrate

The thickness deviation of the pressure plates was 0.09 (3 σ) μm/wafer and the thickness accuracy of 2.15+/-0.35 (3 σ) μm in the mass production stage has been attained. Finally, the rest of the thermal oxide etching mask was fully removed and subsequently the substrate was oxidized thermally in dry O_2 to form 110nm-thick insulator films, then the insulator was removed partially and there Pt common electrodes were deposited selectively as shown in Fig.10(e). A cross-sectional SEM photograph of the cavity substrate is shown in Fig.12.

Assembly Process

The glass substrate fabrication process was basically the same as the first generation SEAJet[1]. After the nozzle substrate, the cavity substrate and the glass substrate were completed by the above-mentioned processes, the SEAJet head was assembled as follows shown in Fig.13: at first the cavity substrate and the glass substrate were anodically bonded together to form highly accurate air gaps, whose length are kept within 0.18+/-0.018 μm as shown in Fig.13(a), then the nozzle substrate was glued to the front side of the cavity substrate, Fig.13(b), the air gaps were sealed by a glue as shown in Fig.13(c). Finally, the substrates were diced into each head chip and its size is W17.1*D12.2*H1.36 (mm^3). The FPC-equipped head chip is shown in Fig.14(a) and the head unit is shown in Fig.14(b).

CHARACTERIZATIONS

The ink drop ejecting velocity and ink drop weight deviated slightly up to 18kHz as shown in Fig.15 and typical values are 6 (m/sec) and 22.5 (ng/drop) respectively at an applied voltage of 26.5V. This represents a great improvement on the first generation SEAJet, which had a maximum ejection frequency of3kHz[1], it has been greatly improved. Deviation of

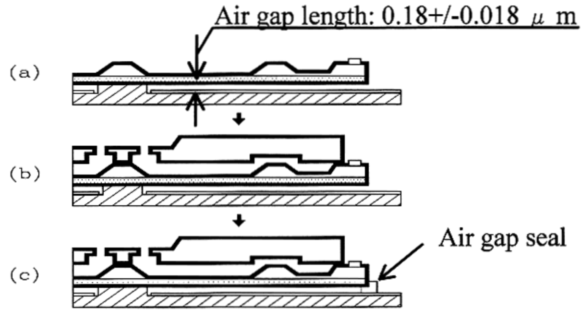

Fig.13: Assembly process of the SEAJet head
(a) Anodic bonding of the cavity substrate and the glass substrate
(b) Gluing of the cavity substrate and the glass substrate
(c) Air gap sealing

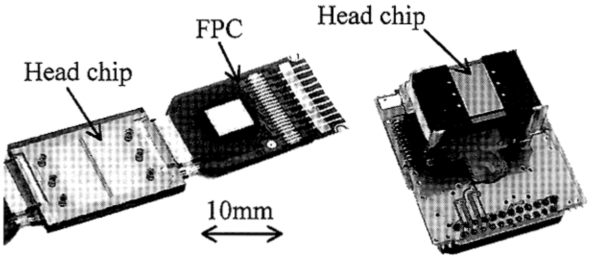

Fig.14: Appearances of (a) the SEAJet head chip attached with FPC and (b) the head unit

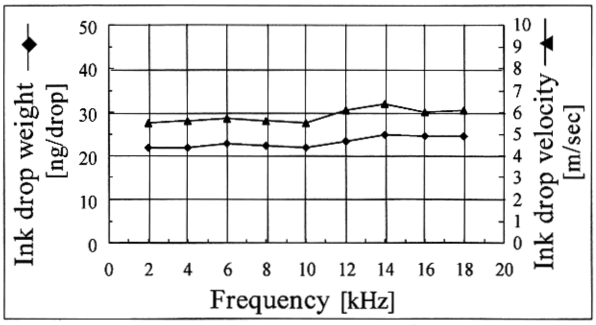

Fig.15: The ink drop ejecting velocity and ink drop weight vs. driving frequency

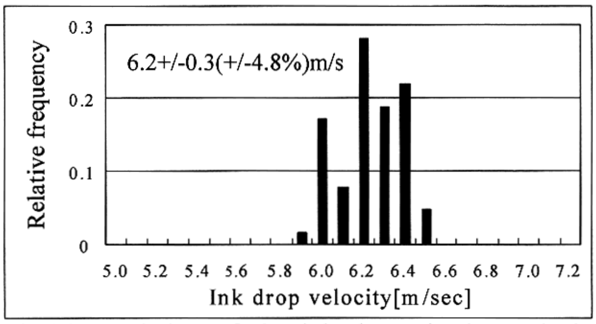

Fig.16: Deviation of the ink drop ejecting velocity among nozzles in a SEAJet head at 25℃

the ink drop ejecting velocity among 128 nozzles in a head is less than +/-5% at 25℃ as shown in Fig.16 and this satisfied the required specifications. The average power consumption was measured as only 0.525mW/nozzle and is only one-thousandth of that of a typical thermal inkjet. Compared with the 3.1mW/nozzle power consumption of the first generation SEAJet, this aspect of the design has also been improved considerably. Durability tests have confirmed the lifetime of the actuator to be more than 4 billion ink ejections. The high resolution SEAJet head enables a printing speed of approximately 15 l/s for a 76mm-wide rolled paper and 3ppm for an A4 size paper. These performances of the high resolution SEAJet marked realization of an inkjet POS printer featuring the highest speed, best print quality and greatest durability of any such printer in the world.

CONCLUSIONS

Newly developed micromachining etching technologies based on B doped etch-stop and ICP deep RIE enable the production of a high resolution, electrostatically driven commercial inkjet head. This has advantages of small size, low power consumption, long lifetime and high printing speed, typically as fast as 3ppm/A4.

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