A LOW POWER, SMALL, ELECTROSTATICALLY-DRIVEN COMMERCIAL INKJET HEAD

S. Kamisuki[1], T. Hagata[2], C. Tezuka[2], Y. Nose[2], M. Fujii[2], and M. Atobe[1]
[1]Production Engineering Department, Seiko Epson Corporation
[2]System Device Division, Seiko Epson Corporation
[1]1010 Fujimi, Fujimi-machi, Suwa-gun, Nagano 399-02, Japan
[2]80 Hirooka-Harashinden, Shiojiri-shi, Nagano 399-07, Japan

ABSTRACT

Si-micromachined electrostatically actuated inkjet head has been developed for the electric calculator printer. It is the first commercial device of this kind.
The electrostatic actuator comprises a Si pressure plate and a corresponding transparent ITO electrode which is parallel to the pressure plate, they are assembled to keep the air gap between them within $0.2 \pm 0.015\ \mu$m. The driving voltage is 38V and a driving frequency is up to 3kHz. The inkjet head have achieved the uniform ink ejection. The weight of an ink drop is kept more than $0.12\ \mu$g under the condition of the frequency range up to 3kHz and the temperature range of 10 to 40℃; this satisfies one of the most critical head specifications.
The calculated average current consumption is only 50 μA / nozzle. Because of the full-batch fabrication and the electrostatic actuation, the inkjet head is low power, thin and small.

INTRODUCTION

Inkjet printers dominate 65% of the consumer market for printers. The main mechanisms of ejecting ink drops are categorized in two groups; one is the thermal type and the other is piezo electric[1,2]. Both heads have their own drawbacks, generally the former consumes too much power to make a large array of nozzles and the thermal actuator has limited life by cavitation damage. In the latter case, generally it is difficult to reduce head size. We have developed a SEA-JET (Static-Electricity Actuator inkJET) which is actuated electrostatically. It is small and fabricated precisely because of batch-micromachining and a simple parallel-plate actuator mechanism. The electric power consumption is very small because it is driven by electrostatic force. Furthermore it is readily scalable to an array of more than 1,000 nozzles in higher nozzle density.
The SEA-JET which is being presented in this paper has 12 edge-ejecting nozzles available on demand (nozzle pitch : 1.97nozzles / mm) and is designed for an electric calculator printer. The mechanism, design consideration, structure, fabrication process and characterizations of the SEA-JET are described in this paper.

MECHANISM OF INK EJECTION

The electrostatic actuator comprises a pressure plate and a corresponding electrode which is parallel to the pressure plate as shown in Fig.1(a), as initial state.
The mechanism of ink ejection is as follows; when DC voltage is applied between the pressure plate and the electrode, the pressure plate is deflected, touches the electrode. Ink flows from the ink reservoir to the ink cavity through the orifice, Fig.1(b). The DC voltage is subsequently reduced to 0. The pressure plate becomes

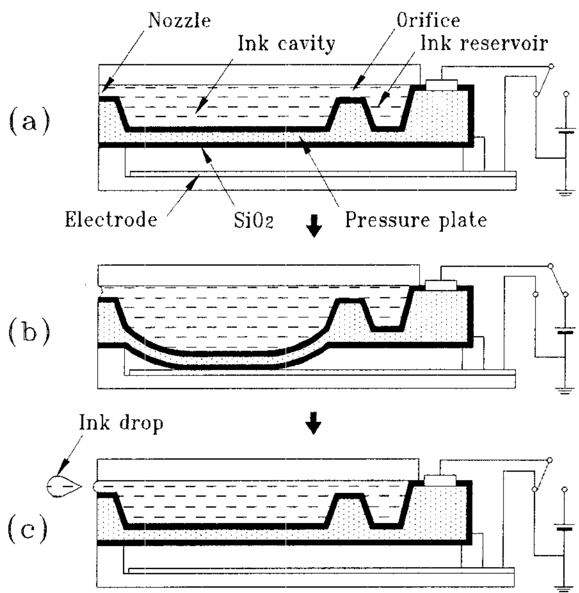

Fig.1 The mechanism of ink ejection (a) initial state (b) DC voltage is applied between the pressure plate and the electrode (c) DC voltage is reduced to 0 and an ink drop is ejected

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flat and an ink drop is ejected from the nozzle because of the increased pressure, Fig.1(c).

DESIGN CONSIDERATION

As the first step of the design, the main specifications of the SEA-JET head were determined by the printer specifications and are as follows;

driving voltage V: 38 (V)
nozzle pitch p: 508 (μ m)
width of the pressure plate W: 367 (μ m)
ink drop weight w: 160 (ng)
ink drop velocity v: 8 (m/sec)
driving (ejecting) frequency f_d: 3 (kHz)
displacement of the actuator Δ Q:3.2 (ncc)

The ink path way and the actuator of the SEA-JET are designed to satisfy the above specifications by an acoustical equation of motion for the SEA-JET head. The model is shown in Fig.2. The simplified equation is given by eqs. (1) and (2)[3]; they describe the state in the time range from the initial state as shown in Fig.1(a) to the DC voltage application state as shown in Fig.1(b) but just before the contact.

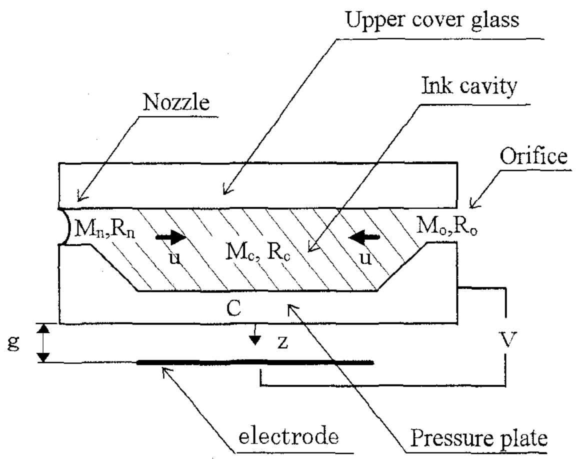

Fig.2 Ink-jet system

$$M\dot{u} + Ru + \frac{1}{C}\int_0^t udt = \frac{\varepsilon}{2}\left(\frac{V}{g-z}\right)^2 \quad (1)$$

$$g - z = \frac{15}{8LW}\int_0^t udt \times 2 \quad (2)$$

$0 < t < t_c$; t_c is the time necessary for the contact of the pressure plate and the electrode

and the initial conditions are as follows;

$$t = 0 ; u = 0, \int_0^t udt = 0$$

where u is the volume flow of ink in the ink path way (the ink path way is composed of the nozzle, the ink cavity and the orifice as in the model shown in fig.2); the volume flow means the flow of ink per unit of time in the ink path way. M is the acoustical mass of the overall ink path way and R is the acoustical resistance of the overall ink path way. They are fixed as eqs. (3) and (4) as follows;

$$M = (Mn + Mc + Mo) / 2 \quad (3)$$
$$R = (Rn + Rc + Ro) / 2 \quad (4)$$

where Mn , Mc and Mo are the acoustical mass of the nozzle, the ink cavity and the orifice respectively. They are determined by the shapes and dimensions of the corresponding ink path way and the ink density. Also, Rn, Rc and Ro are the acoustical resistance of the nozzle, the ink cavity and the orifice respectively; they are determined in similar way as Mn , Mc and Mo. C is the acoustical capacitance of the pressure plate, ε is the dielectric constant of the air , g is the length of the air gap, z is the deflection of the Si pressure plate and L is The length of pressure plate.
Natural frequency f_n of the SEA-Jet head model is given by eq. (5)[4].

$$f_n = \alpha \times f_d \cong \frac{1}{2\pi}\sqrt{1/MC} \quad (5)$$

Although the combinations of Mo, Mn, Ro, Rn and C can exist innumerably, we have adopted the following values:

$$M = 2\times10^{8} (kg / m^4)$$
$$R = 6\times10^{12} (N\cdot s / m^5)$$
$$C = 2\times10^{-18} (m^5 / N)$$

based on the capacity of the fabrication process and past data.
Solving eq. (2) by using these values, the length of the air gap g is derived as;

g = 0.2 (μ m)

The length of pressure plate L is derived from displacement of the actuator Δ Q, the length of the air gap g and the width of the pressure plate W as follows;

L = 8.2 (mm)

The dimensions of the orifice and the nozzle, and the number of orifices No are determined to satisfy M, R and the ink drop velocity v as follows;

Lo = 300 (μ m), Ho = 39 (μ m)
Ln = 10 (μ m), Hn = 43 (μ m)
No = 5

where Lo and Ln are the length of the orifice and the nozzle respectively, Ho and Hn are the height of the cross sectional triangle of the "V groove" orifice and nozzle respectively.
The thickness of the pressure plate T is calculated by the value of C and the width of the pressure plate W as follows;

T = 13 (μ m)

SEA-JET STRUCTURE

A SEA-JET chip has a size of $9 \times 11 \times 2.1$ (mm^3). Figure 3 is its photograph. It is composed of a three-layer structure including (1) an upper cover of glass substrate, (2) a Si substrate and (3) a lower glass substrate as shown in Fig.4, and the whole appearance of the assembled SEA-JET is illustrated in Fig.5.

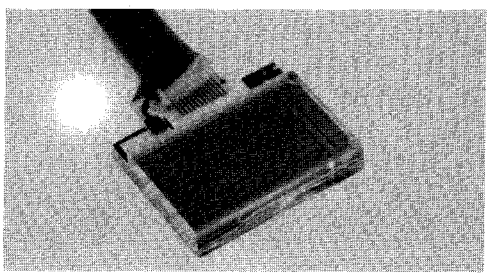

Fig.3 Photograph of the SEA-JET chip

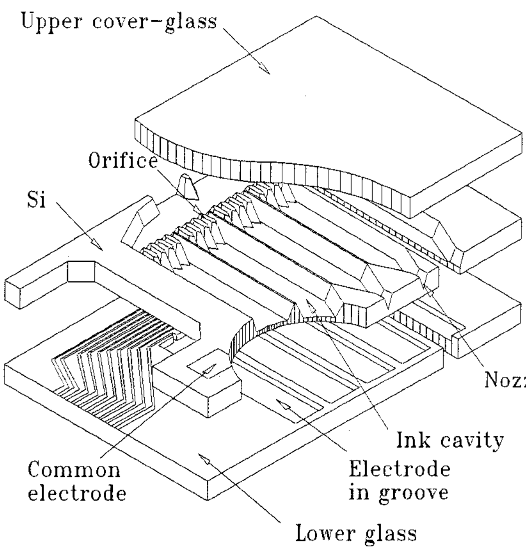

Fig.4 Three-layer divided diagram of the SEA-JET

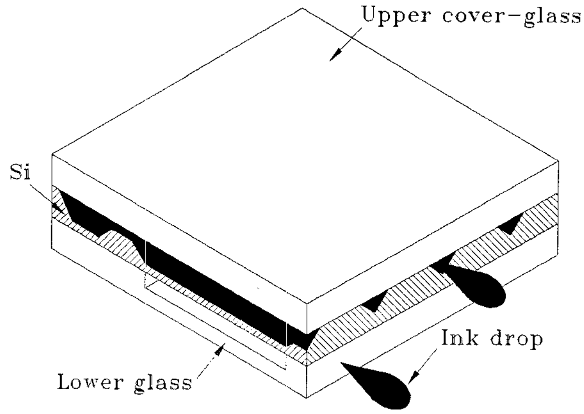

Fig.5 Diagram of the assembled SEA-JET

Pressure plates, nozzles, orifices and an ink reservoir are formed on the Si substrate. The lower glass substrate contains grooves and there are ITO electrodes in each groove. The upper glass covers the nozzles, orifices and an ink reservoir.
Because the length and tolerance of the air gap of the electrostatic actuator are very tight at $0.2 \pm 0.015\,\mu$m as derived by the design consideration. As a results, we chose Si and Pyrex glass as the materials for the attainment of the air gap accuracy and used the anodic bonding.

FABRICATION PROCESS

The fabrication process of the SEA-JET consists of the Si substrate process, the lower glass substrate process and the assembly process, shown in Fig.6(a)-(c) respectively.

Si substrate process
First, a 100 μ m-thick, (100) oriented Si substrate is prepared and 1 μ m-thick thermal oxide films are formed on the both sides of the substrate as in, Fig.6(a1).
The front-side thermal oxide film is etched to have a pattern corresponding to the components including pressure plates, the orifices and the ink reservoir. Next, the Si substrate is etched in a KOH solution and etching is stopped when the thickness of the pressure plate becomes 13 μ m. All other components are formed simultaneously as Fig.6(a2).
A reagent is added to the KOH solution in order to smooth intermediate crystal planes between the two (111) planes which emerge at the interconnection between the nozzle and the ink cavity wall. Finally, the substrate is thermally oxidized and a common electrode is formed on the front side of the substrate as shown in Fig.6(a3). SEM photographs of the nozzles

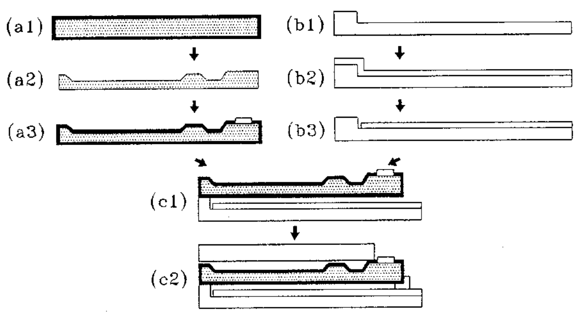

Fig.6 SEA-JET fabrication process

(a) Si substrate process

(a1) Thermal oxidation, (a2) Wet anisotropic etching, (a3) Final thermal oxidation for electrical isolation

(b) Lower glass substrate process

(b1)Wet etching, (b2) ITO deposition, (b3) ITO patterning into the individual electrodes

(c) Assembly process

(c1) Anodic bonding of Si substrate and the lower glass substrate, (c2) Anodic bonding of Si substrate and the upper cover of glass substrate

and the orifices are shown in Fig.7(a) and (b) respectively.

Lower glass substrate process

First, a 1mm-thick, Pyrex glass (Corning #7740) substrate is prepared and a metal film as an etching mask is sputter-deposited on the front-side of the glass substrate. Then the metal film is etched to have a pattern of the air gap which is corresponding to the Si pressure plate. Next, the glass substrate is etched and etching is stopped when the depth of the etched area becomes 0.3 μ m. The metal film is removed as shown in Fig.6(b1). Then a 0.1 μ m-thick ITO film is deposited on the glass substrate, Fig.6(b2), and patterned to the individual electrodes. Subsequently the length of the "air gap" becomes 0.2 μ m, Fig.6(b3). An SEM photograph of ITO electrodes and the etched grooves is shown in Fig.7(c). Due to the transparency of the ITO electrodes, inspections of the air gap (contamination, the length of the air gap and the flatness of the Si pressure plate) are easily performed from the "back side" direction of the lower glass substrate.

Assembly process

The Si substrate and the lower glass substrate processed as described above are anodically bonded together after the pressure plate and the corresponding ITO electrode are aligned, Fig.6(c1). The upper cover of the glass substrate is also anodically bonded to the Si wafer by the same condition as the former anodic bonding, Fig.6(c2).

Because the lower glass substrate and the Si substrate are anodically bonded, the lengths of the air gaps are exactly defined and the performance of the electrostatic actuator is permanently stable. Also, because the upper cover of the glass substrate and the Si substrate are anodically bonded, the dimensions of the nozzles and the orifices are exactly defined and therefore the performance of the ink ejection will be uniform among the nozzles.

Furthermore, the assembled substrates are divided into each head chip by dicing. The "nozzle surface" is polished, cleaned and "water-repellent" film is deposited in order to make the ink ejection velocity faster and to always keep the direction of the ink ejection straight. An SEM photograph of the nozzle surface and a photograph of the SEA-JET head unit are shown in Fig.7(d) and (e) respectively.

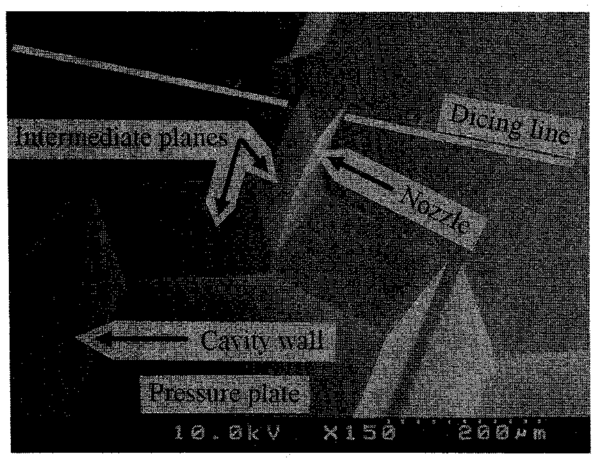

Fig.7(a) SEM photograph of the nozzles and the pressure plates

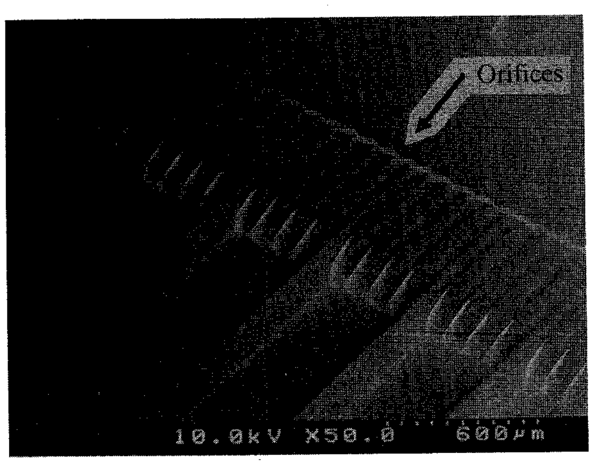

Fig.7(b) SEM photograph of the orifices and the pressure plates

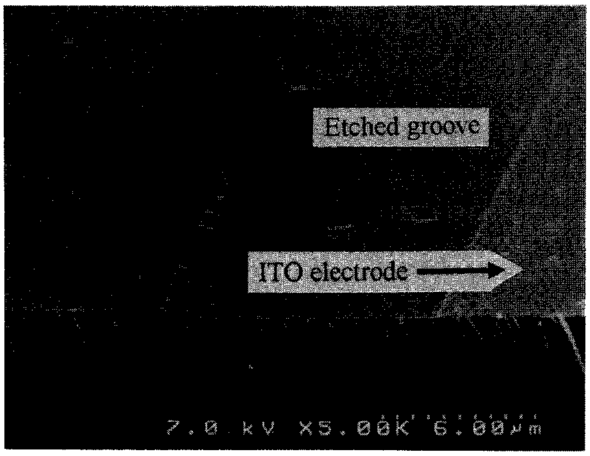

Fig.7(c) SEM photograph of the ITO electrodes and etched grooves

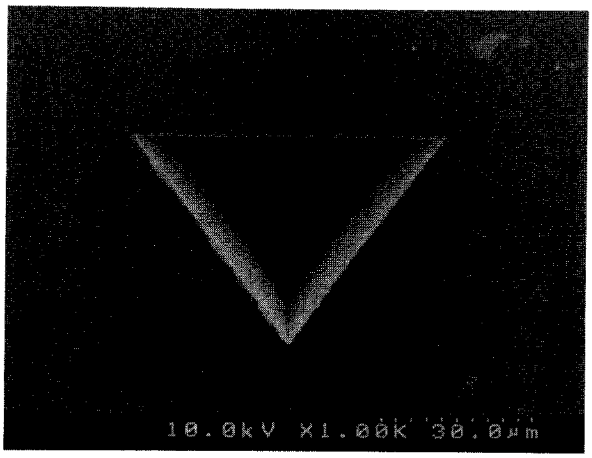

Fig.7(d) SEM photograph of the nozzle surface

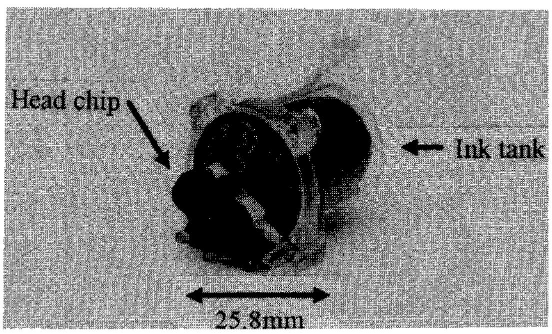

Fig.7(e) A photograph of the SEA-JET head unit

CHARACTERIZATIONS

The relation between an ink drop weight and a actuating voltage is shown in Fig.8(a). Typical value is 0.16 (μg / drop) at an applied voltage of 38 V. It depends only slightly on the applied voltage.

The specification of the weight of ink drop is that it is guaranteed at more than 0.12 (μg / drop) for both frequency ranges up to 3kHz and temperature ranges of 10 to 40℃. Figure 8(b) represents plots the weight of an ink drop as a function of ejection frequency. The variation of the weight of an ink drop is less than 10% at any frequency range up to 3kHz. In a frequency region higher than 1.7kHz, the weight of an ink drop is intentionally decreased in order to achieve proper printing density. Figure 8(c) shows the relation between the ink drop weight and temperature. Although the weight of the ink drop goes up according to a rise in temperature because of the decrease in ink viscosity, it is kept in the range described above.

The state of ink drop flight is shown in Fig. 9. It is seen straight ejection is attained.

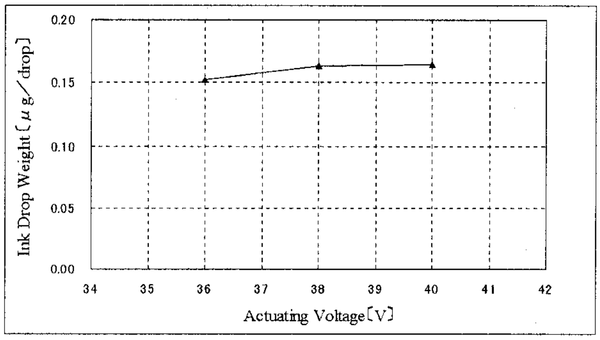

Fig.8(a) Ink drop weight vs. Actuating voltage

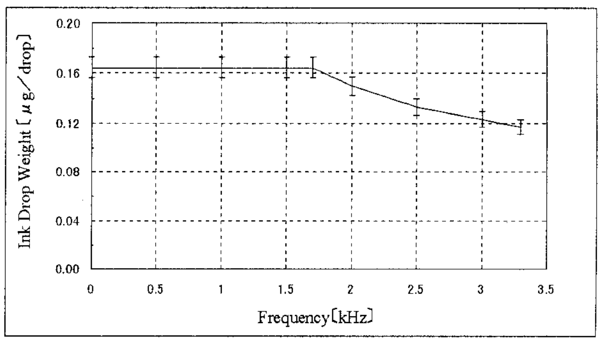

Fig.8(b) Ink drop weight vs. Ejecting frequency

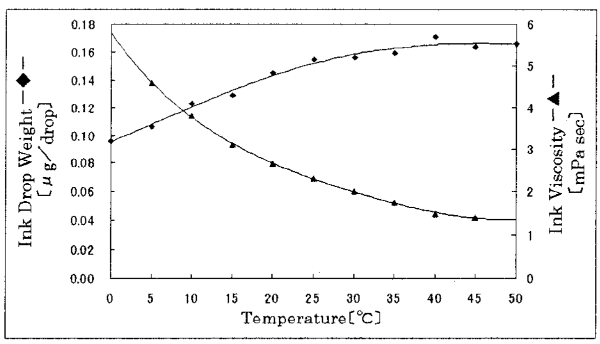

Fig.8(c) Ink drop weight vs. Temperature

As an important characteristic, the average current consumption is only 50 μ A/ nozzle (calculated value) which is much smaller than that of a thermal inkjet [5]. Also, tests have confirmed the lifetime of the actuator is more than 1 billion ink ejection, although the ink tank capacity is only 2 million ink drops.

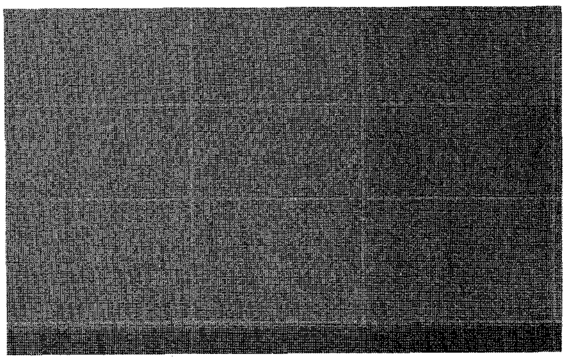

Fig.9 A state of ink drop flight

CONCLUSIONS

A thin and small inkjet head named the SEA-JET has been developed. Because Si and glass substrates are used, sufficient rigidity and high preciseness are attained. Moreover since Si and glass are thermally and chemically durable, it is possible, in principle, to eject low melting-point metals such as a solder. The variation of ink ejection performance (ink drop weight) is less than 10% at any frequency. Because of the simple construction of the electrostatic actuator, the SEA-JET can be fabricated in a low cost process.
Furthermore, higher frequency ink ejection in a higher nozzle density has been already confirmed for a next-generation SEA-JET.

REFERENCES

[1] T.Hara and I.Endo, "Bubble Jet Recording", J. The Institute of Image Electronics Engineers of Japan, Vol.11, No.2, pp.66, 1982 (in Japanese)

[2] E.L.Kyser, "Method and Apparatus for Recording with Writing Fluids and Drop Projection Means Therefor", U.S.Patent, 3,946,398, 1976

[3] D.J.IJntema and H.A.C.Tilmans, "Static and dynamic aspects of an air-gap capacitor", Sensors and actuators A, Vol.35, pp.121, 1992

[4] M.Nishimaki, "Electro-Acoustics and Vibrations", Corona Publishing Co.,Ltd. 1960, 1978 (in Japanese)

[5] J.Chen and K.D.Wise, "A High-Resolution Silicon Monolithic Nozzle Array for Inkjet Printing" IEEE TRANS. ELECTRON DEVICES, Vol.44, No.9, pp.1401, Sept.1997