Development of a Femtoliter Piezo Ink-jet Head for high resolution printing

Kin'ya Ozawa, Takahiro Usui, Katsuya Ide, Hayato Takahashi, Shinri Sakai; Seiko Epson Corporation; 281 Fujimi, Fujimi-machi, Suwa-gun, Nagano-ken, 399-0293, Japan

Abstract

Inkjet printing technology is used in the manufacture of color filters and alignment layer film for liquid crystal displays. The minimum droplet volume is achieved under a few picoliters and the head prints lines of a few tens of micrometers. In order to expand range of applications of the inkjet technology, we consider that a inkjet head is needed with the ability to micropattern feature sizes of 10 micrometers. The size of features depends mainly on the volume of ink contained in droplets fired from an inkjet head. This work presents a new inkjet head comprising piezoelectric actuators that fires droplets having a volume of less than 1 picoliter. Examples in which the inkjet head was used to directly deposit ink droplets to micropattern devices are described. An efficient approach has been taken to develop the inkjet head so that the head structures are optimized and micro-droplet behavior is controlled. The inkjet head is found to be capable of firing 500-femtoliter droplets and forming micropatterns on a substrate. The droplets exhibit a stable, straight flight path.

Intoduction

Inkjet printing is a familiar method for transferring electronic data to paper and for forming photo-like prints, and inkjet printers are standard equipment in every office and household. On the other hand, Inkjet printing has been expanding its application area where a variety of functional materials such as polymers and metals are deposited in the form of ink containing these materials to fabricate electronic devices.

Today, inkjet fabricated multicolor polymer light-emitting diodes, metal lines and liquid crystal displays are well known examples of the new application area of the inkjet technology [1, 2]. Additionally, the scope of application is widely believed to have untapped market. One of the major challenges in inkjet printing is to develop a system capable of firing the very small droplets needed to draw narrower lines on substrates.

Seiko Epson has been focusing on the development of piezoelectric inkjet technology that produces high-resolution, high-quality prints on paper using a Multi-layer Actuator Head (MACH) that is driven with a piezoelectric element. The ejection of droplets as small as 1.5 picoliters has enabled extremely high dot density marking with reduced dot-to-dot spacing. In addition, Variable Sized Droplet Technology (VSDT) [3], which enables the discharge of three different sizes of droplets (small, medium and large) from the same nozzle by changing a driving waveform, has evolved to the extent that the different sized droplets are selectively discharged according to input image data, thus boosting printing speed.

Many researchers use an inkjet process to deposit nano-metal particles to produce circuit boards and flat-panel displays. Most of these processes use common inkjet heads that can fire droplets having a volume on the order of several picoliters. As a result, the widths of drawn lines the head can draw are in the range of a few tens of micrometers to hundredths of micrometers. Screen-printing can also draw linewidths on this same order. On the other hand, photolithography techniques can be used to form linewidths measuring several micrometers or less. The disadvantage with photolithography is that expensive photo-masks must be prepared for each pattern, thus adding to device cost.

In the printer business, dots created using droplets having a volume of 1 picoliter or less are not considered intense demands, as the human eye is incapable of resolving dots this small. In device manufacturing, however, droplets of less than 1 picoliter have great value. A 1-picoliter droplet has an estimated diameter of 15 micrometers or less after landing on a substrate. Taking wetting on substrates into consideration, the width of a line drawn with 1-picoliter droplets grows to 30 micrometers or more (Figure 2). Inkjet-drawn linewidths of 10 micrometers or less are considered to be the threshold beyond which applications will expand.

The purpose of our work was to develop a new inkjet head capable of discharging a femtoliter-order droplet. In addition, to characterise the developed print heads, performance and quality of drawn lines were examined.

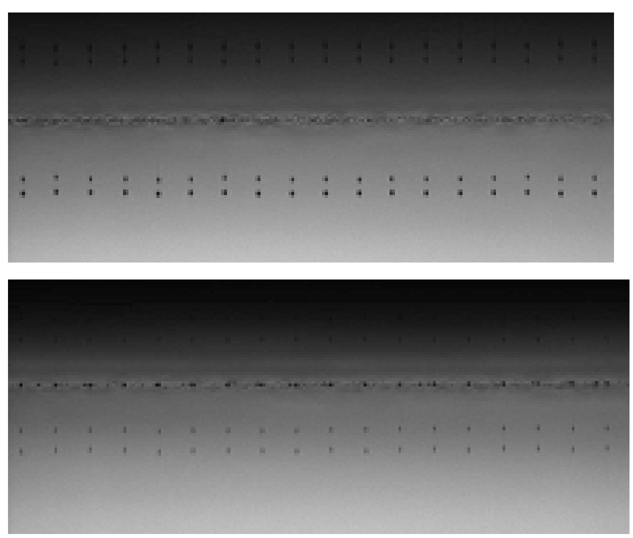

Figure 1. *The flight image of 4000-femtoliter droplets(upper) and 500-femtoliter droplets(lower).*

Head design

Drop size modulation demands consideration of many parameters, such as hydrodynamics, head structure and driving waveform. Therefore, we first performed a flow simulation. The simulation was performed with FDM to clarify whether or not femtoliter-order droplets could be fired [4, 5].

We indicate the intention to reduce the volume. Small volume makes the flight speed V decrease. Therefore, characteristic vibration period of a pressure chamber T_c needs to be reduced , or a cross section area of nozzle A to be smaller. If ink volume Q is reduced to a third part of a current volume, the product of T_c and A also have to be a third part the current one to keep the flight speed unchanged. We reduced a nozzle diameter and as a result, A became smaller. We made several type print heads , which have different size of nozzle opening diameter down to as small as a half of the standard nozzle size.

The simulation was applied again to the new inkjet head for optimizing a driving waveform which can eject very small droplets. We predicted, based on the simulation, that the motion of the meniscus in the nozzle orifice would enable the discharge of a femtoliter-order droplet.

Figure 4 shows a motion of the meniscus in an orifice at different times in the firing cycle. The colors in the figure indicate velocity magnitude in the orifice during droplet formation. In the first step, the meniscus is greatly pulled into the orifice and a concave shape is formed at the center portion of the meniscus converged ink flow to the center part of the meniscus generates a convex portion where the fluid velocity is high.In the second step, converged ink flow to the center part of the meniscus generates a convex portion where the fluid velocity is high, generating a small droplet due to the inertia force. This technique enables the ejection of droplets that are smaller than the diameter of the orifice.

This meniscus control technique in conjunction with the piezo type print head is extreamly effective to reduce droplet size [3]. Hence we have calculated the optimal pulse timing to enable the firing of droplets having a volume less than 1 picoliter. The simulation results thus reflected to the actual head with a higher level of certainty than is possible with other techniques.

Inkjet heads were manufactured with designed by the simulation. To reduce droplet size, the head structure was reexamined and optimized. The functions of high-density nozzles and VSDT were maintained. The resulting inkjet head fires femtoliter droplets with a high throughput. Figure 1 shows the flights of 4000-femtoliter and 500-femtoliter droplets. The most remarkable feature of the results is that the flight of femto-order droplets is extremely stable. The 500-femtoliter droplet is so small that the image has lower contrast than that showing the 4 picoliter droplets.

Head performance

The inkjet head was produced based on the simulation and the predicted droplets were fired from the nozzle orifices. The flight of droplets, divided into main and satellite droplets, was extremely stable. Droplet volume from each nozzles appeared to be uniform. Once they ejected from the nozzle, femtoliter-order droplets are more susceptible to air resistance than 4-picoliter droplets. In actual use, sufficient flight straightness is required. with a platen gap between 500 micrometers and one millimeter, without significant drop of the deposition speed. As you can see in Figure 5, droplet flight is thus stable at 1 millimeter. High-speed

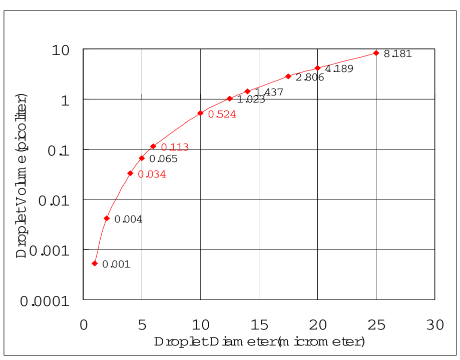

Figure 2. *Droplet volume vs droplet diameter.*

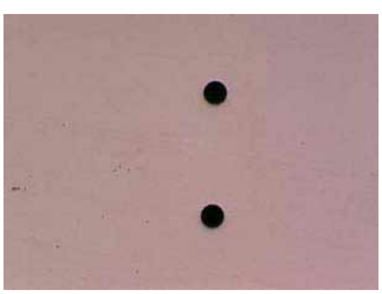

Figure 3. *The image of nozzles.*

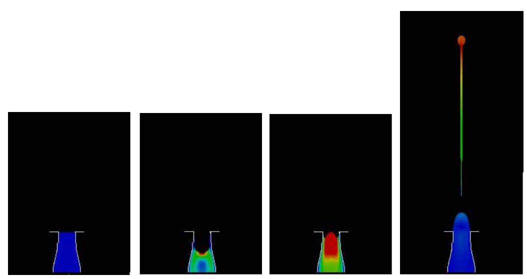

Figure 4. *Simulation of drop formation*

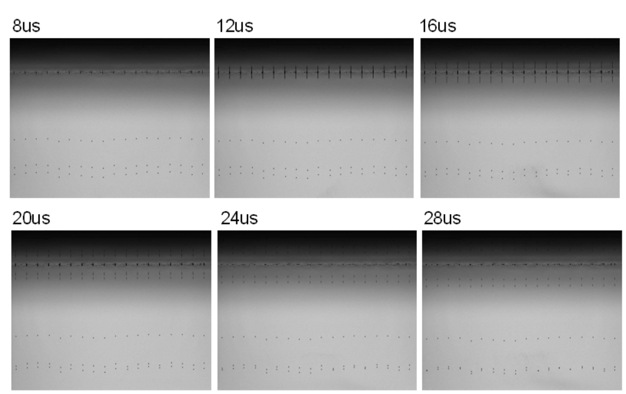

Figure 5. *: Formation of a femtoliter-order droplet in different time-steps.*

observation shows that drop formation is modulated by variations in the driving waveform. A means of controlling satellite droplets so that they travel along a straight path is considered vital for discharging femtoliter-order droplets.

The new inkjet head has been tested, and the droplet speed variations were measured across different frequencies and driving voltages. The results are shown in Figure 6 and Figure 7, respectively. Figure 6 shows the interrelationship among driving voltage, flight speed, and flight weight. Driving voltage and flight speed, and driving voltage and droplet weight have a primarily linear relationship. The fight speed was measured at a point where the droplets reached a distance of 500 micrometers from the nozzles. Droplets with a volume of 400-500 femtoliters reached a speed exceeding 10 meters per second. This speed is sufficiently high for accurate printing. When driving voltage is on the low end of the scale, flight velocity decreases to less than five-meters per second and ink weight decreases to less than 300 femtoliters. It is difficult to characterize a head that ejects 300-femtoliter droplets, because the flight velocity is too low to achieve accurate droplet placement over a substrate.

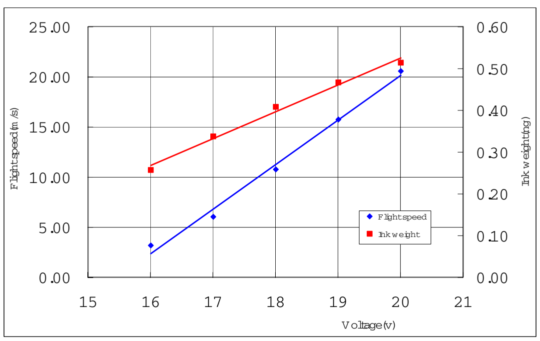

Figure 6. Measured drop volume and drop speed as a function of driving voltage

Moreover, figure 7 shows the results of firing weight as a function of frequency. A lower driving frequency results in reduced printing throughput. This inkjet head can fire stably at up to 25 kHz.

Results

The new inkjet head has many potential applications in device manufacturing. In particular, we expect inkjet systems that employ the new head to be used in metal wiring deposition applications. For this reason, we experimented with the printing of narrow lines.

Figure 10 shows results of dots deposited on an absorbent media using the new inkjet head. Three-picoliter droplets have a 40-micrometer diameter after landing. A 500 femtoliter droplet corresponds to a 20-micrometer diameter. A droplet that has a diameter of 10 micrometers in flight produces, after landing on a medium, a dot twice that size. If a non-absorbent medium is used, the dot diameter depends mainly on surface wetting, and wetting is determined by medium surface treatments [6]. A 10-micrometer linewidth, achieved without substrate surface treatments, is desirable. Our findings indicate that an inkjet head must produce very small droplets.

We used a head that fires 3-picoliter and 500-femtoliter droplets to print continuous lines on an absorbent media. Figure 8 and Figure 9 show the results. The 500-femtoliter droplets are too small to bridge space between dot pitch.As a result, a sharper outline of dots was produced .

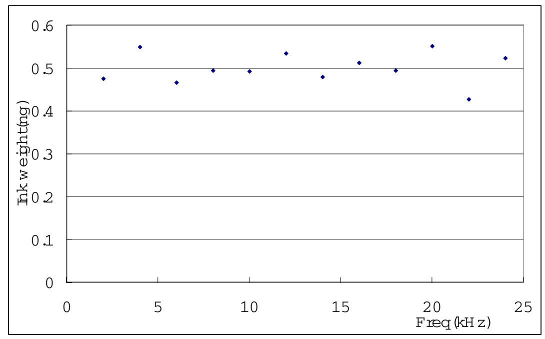

Figure 7. Measured frequency as a function of orifice number.

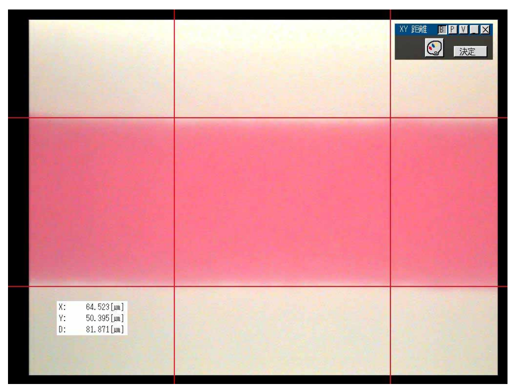

Figure 8. Drawn line after 3-pl droplet deposition

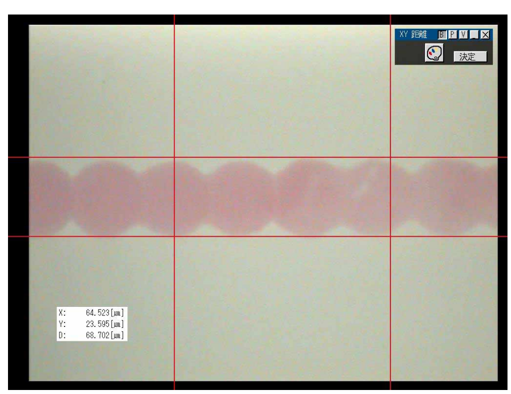

Figure 9. Drawn line after 500-fl droplet deposition

Conclusion

We have developed a new Piezo inkjet head capable of firing femtoliter droplets. The head has manufactured based on the simulation and driving waveforms has also optimized by the simulation. Droplet flight is extremely stable at high-frequency operation. Moreover, the inkjet head has a high-density nozzle array, and can be expected to provide high throughput. The minute femtoliter droplets produce narrower linewidths on a substrate than do picoliter-order droplets. The new head can draw narrow lines which have a width down to 20 micrometers using 500 femtoliter droplets. The experimental results using the print head indicated about 100 femtoliter droplet is required to draw linewidths of 10 micrometers without special substrate surface treatments. The technology described in this paper will lead to the expanded applications of inkjet technology in manufacturing electronic devices.

References

[1] T. Shimoda, M. Furusawa, et.al. Nature, 440, 783-789, 6 April, (2006)

[2] E. Shioya, T. Kamakura, et.al. SID06 Digest 48.1(2006)

[3] T. Kitahara, Japan Hardcopy 1999, 335 (1999).

[4] Shinri Sakai, Dynamics of Piezoelectric Inkjet Printing Systems. Proc. IS&T NIP16, pp. 15-20(2000).

[5] Jiun-Der Yu and Shinri Sakai, Piezo Ink Jet Simulations Using the Finite Difference Level Set Method and Equivalent Circuit, Proc. IS&T NIP19, pp. 319-322(2003).

[6] Toshimitsu Hirai and Hiroshi Kiguchi, Surface Modification Technology for Inkjet Industry, Proc. DF2006, pp. 46-50(2006).

Author Biography

Kinya Ozawa received his MS in applied physics from Tokyo Institute of Technology (1996) and his PhD in applied physics from Nagoya University, Japan(2007). He is the chief engineer of IJP Key Components R&D Department, Seiko Epson Corporation. His primary responsibilities are designs and analysis for inkjet technology and micro liquid process.

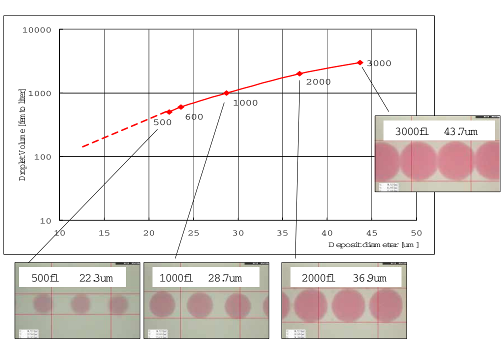

Figure 10. *Measured drop volume and drop diameter on paper.*