# Lateral Merging Continuous Inkjet

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## Abstract

*Continuous inkjet (CIJ) devices that use more than one nozzle to form a single droplet are reported. The experimentally studied devices contain a pair of interactive nozzles that are used to form ink drops with large and small volumes by thermally stimulating a liquid jet at each nozzle, causing controlled breakup. Resistive heaters located around each nozzle are used for both thermal stimulation and for controlling the direction of the ink stream from each nozzle. Under proper conditions, the large drops formed from each nozzle in the pair touch each other and merge laterally, while the small drops from each pair of nozzles remain separate. The lateral merging CIJ system offers a potential for even greater speed advantages and higher image quality than existing single-nozzle Kodak Stream inkjet technology, a continuous inkjet system. Details on design, fabrication, and characterization of the lateral merging CIJ device are provided, including results from experimental studies.*

## Introduction

Continuous inkjet (CIJ) technology offers potential advantages of higher print speed, increased reliability, and lower cost of ownership compared to drop-on-demand (DOD) inkjet technology. The Stream drop generator is a silicon-based microelectromechanical system (MEMS), fabricated with integrated CMOS drivers and associated circuitry [1-4]. Typical operation of the printhead involves generation of small and large drops of fluid via jet breakup controlled by low-energy pulses applied periodically to a heater situated around each jet orifice [5]. The drops are then sorted using an air cross-flow, with the small nonprint drops sent to the gutter for recirculation, and the large print drops sent to the print media [6].

Typically, a volume ratio of at least 3:1 between the larger print drops and the smaller nonprint drops is used. Under this condition, the small drops are 1X fundamental drops formed using a stimulation frequency and velocity such that the jet wavelength ($\lambda$) is about 4.5 times the nozzle diameter. The larger 3X drops have a wavelength of 3 $\lambda$ and a large drop formation length (LDFL) that is much greater than the break-off length (BOL) of the 1X fundamental drops. It is desired to have the LDFL and BOL as short as possible in order to minimize the overall distance to the print media. It is also desired to have the mass ratio between the large print drops and smaller 1X nonprint drops as large as possible to achieve high spatial separation for drop selection using the cross-flow of air.

Continuous inkjet technologies using asymmetric heating of a jet to cause deflection, i.e., thermal steering, have been studied previously [7]. Researchers have demonstrated that a heating pulse provided to the left side of a jet causes the jet to be deflected to the right (away from the heat pulse) [7]. The deflection mechanism is caused by changes in viscosity and surface tension of the jetting fluid induced by the thermal pulse [7,8].

The lateral merging Continuous Inkjet technology is similar to the Stream CIJ technology in that it generates large and small drops via controlled breakup [9]. However, unlike previous CIJ architectures, it employs thermal stimulation and thermal steering to cause the drops from a pair of nozzles to merge laterally to form large drops. A comparison of the lateral merging CIJ to Stream CIJ operation (3:1 ratio) is shown in Figure 1. The 2 × 2 large drops shown are the result of a 2X drop formed by each nozzle merging laterally to form a single 2 × 2 drop, which is effectively 4 times the volume of the 1x small drops. The distance between the 2 nozzles in the nozzle pair is set such that the small 1x drops do not merge but the large 2X drops do merge laterally.

In operation, the lateral merging large drop (2 × 2 drop) wavelength is 2 $\lambda$; therefore, the LDFL is very short and difference between the BOL and LDFL is minimized. Because of lateral merging, the large drop is 4 times the size of the small drop, which should provide better drop separation than a 3:1 ratio with a single nozzle. The 2 × 2 drops also provide a print speed advantage over 3X large drop print mode due to the increased frequency of print drop formation. The reduction in LDFL should also bring gains in image quality by reducing the throw distance from the nozzle plate to the receiving media.

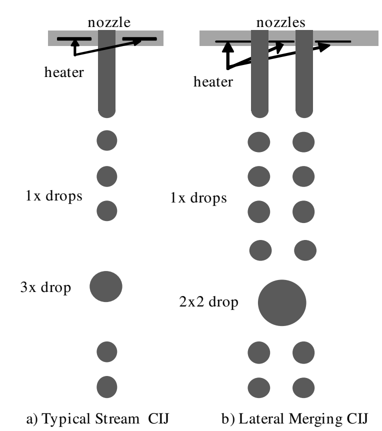



***Figure 1**. Comparison between Stream CIJ and lateral merging CIJ.*

## Device Design and Fabrication

The lateral merging experimental devices were designed such that the effects of nozzle diameter ($D_{Nozzle}$) and nozzle spacing could be studied systematically. As shown in the cross-sectional view of the lateral merging devices in Figure 2, $D_{Nozzle}$ was varied, chip to chip, from 6.5 µm to 9 µm in 0.5 µm increments.

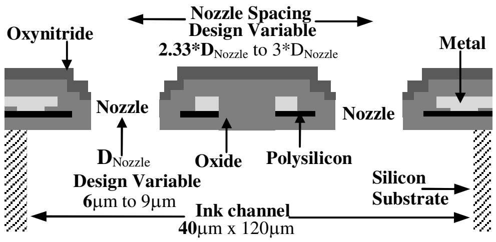



***Figure 2.*** *Cross-section of the lateral merging device having a nozzle pair in a single ink channel with critical dimensions is shown.*

On each chip there were 7 lateral merging devices, each having two nozzles of the same $D_{Nozzle}$ per ink channel with each pair working as one effective nozzle. The spacing between the lateral merging nozzles within the ink channel was varied device to device ranging from 2.33* $D_{Nozzle}$ to 3* $D_{Nozzle}$; each nozzle pair is centered with their respective ink channel. There was one ring heater device on each chip having the same diameter as the nozzles of the lateral merging devices for comparison. There are 9 active effective nozzles per chip spaced 300 µm apart (center to center).

In order to employ thermal steering, the lateral merging nozzles pairs were designed so that each nozzle has a split heater where the inside and outside heaters are connected in series. Practically, the outside heaters are driven simultaneously to steer the jets toward each other, and the inside (between the nozzles) heaters are also driven simultaneously to steer the jets apart. The shape and location of the heater elements are shown in the micrograph in Figure 3.

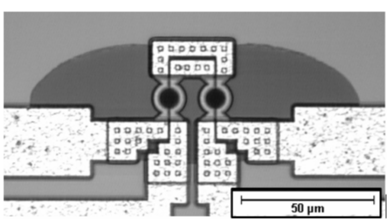



***Figure 3.*** *Top view micrograph of lateral merging device.*

The heaters for the lateral merging devices were fabricated from polysilicon using standard processes on 675 µm thick wafers. The heaters were sized so that the resistivity of the heaters is constant for all design variations. The nozzle membrane was formed from a dielectric film stack (2.6 µm thick), and the nozzles were etched in alignment to the heaters; the offset from the edge of the nozzle to the heater edge was held constant at 0.8 µm. The silicon wafers were thinned to 350 µm, and the ink channels (40 µm × 120 µm) were etched in silicon by the anisotropic deep reactive ion etch (DRIE) process [9].

## Experimental

The lateral merging chips were packaged such that the backside channels were in fluidic communication with a pressure vessel used to provide fluid to the nozzles. The bondpads were wirebonded to a PGA and driven by an arbitrary waveform generator and a voltage source. Images of drop formation were captured using typical stroboscopic techniques.

Initial pressurization of a lateral merging device showed the propensity for the fluid streams to merge downstream of the nozzle plate. The 0 V micrograph of Figure 4 illustrates typical observed behavior. The ability to use thermal steering was evaluated by applying increasing levels of voltage (stimulation) at high duty cycle (99%). As seen in Figure 4, the streams can be driven from a condition of convergence, through a condition of parallelism, to a condition where the streams diverge simply by increasing the power provided to the inside heaters. This is consistent with the results discussed earlier from the single-nozzle thermal steering devices.

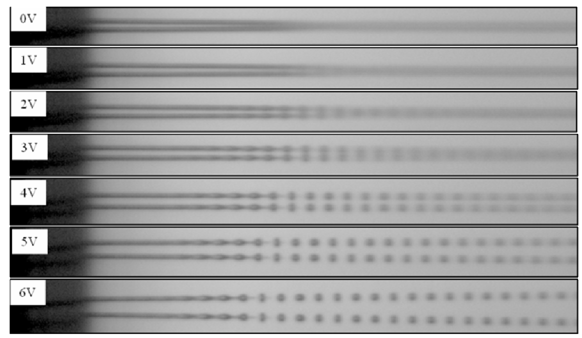
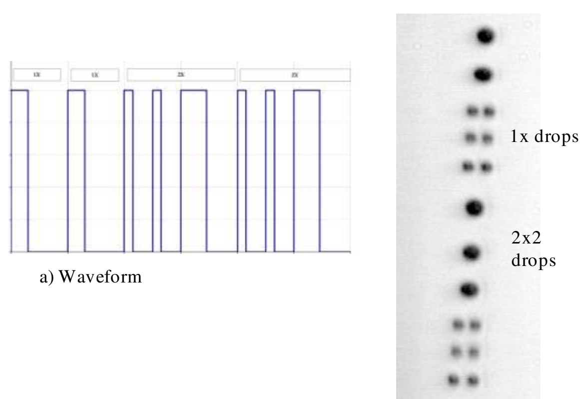



***Figure 4.*** *Images of fluid jets being deflected at various power levels.*

Revisiting the lateral merging device design, the inside heaters are connected in series and outside heaters are connected in series in order to steer the drops together or apart, respectively. A simple waveform, shown in Figure 5 a), was used to test the effectiveness of the thermal steering when used to form 1X and 2 × 2 drops. In the study the inside and outside heaters were used in phase with the same waveform but different amplitude. The voltage on the outside heaters held fixed at values from 1 V to 5 V; the voltage required to form separate 1X drops was recorded. For all nozzle pairs it was possible to form separate 1X drops and merged 2 × 2 drops with this methodology (up to the limit on the power supply).




b) Micrograph of Lateral Merging CIJ drops 2mm from the nozzle plate

***Figure 5.*** *Representative waveform used to drive the lateral merging devices is shown in a); good agreement was seen between expected and actual results as seen in b).*

Figure 5 b) illustrates drops formed by a representative nozzle pair having $D_{Nozzle}$ = 9.0 μm, a spacing factor of 2.78 operated using the representative waveform illustrated in 7 a) with an amplitude of 4 V on the outside heaters and 7.5 V on the inside heaters. As expected from the design, a large voltage/energy on inside heaters pushes drops apart, and conversely large voltage/energy on the outside heaters pushes drops together. However, as can be seen from the data in Figure 6, non-merging small drop formation requires large voltage on inside heaters if there is a voltage on outside heaters.

Figure 6 also illustrates that the nozzles get closer together as the energy required to separate the 2 streams of 1X small drops increases. Additional testing was completed using the representative waveform with no voltage applied to the outside heaters. It was determined that the outside heaters were unnecessary to form small and large drops with this experimental design. The remaining characterization of the lateral merging CIJ devices was conducted using only the inside heaters. This ability to stimulate from a single heater pair has the benefit of requiring only one electrical connection per nozzle pair, thus making it consistent with current Stream and other single-nozzle devices.

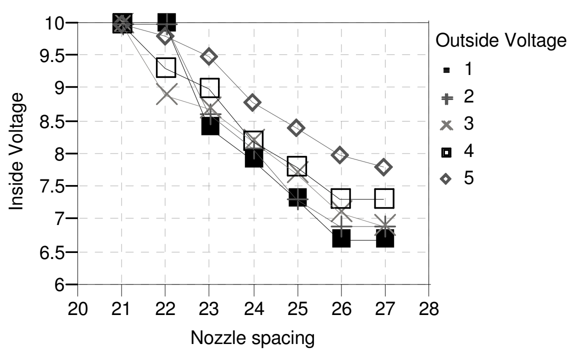



***Figure 6.*** *Energy required to achieve separate small drops increases as nozzle spacing decreases.*

The large drop formation length (LDFL) and break-off length (BOL) were assessed for the lateral merging devices and compared to data from a single-nozzle device of equivalent diameter. Using the single-nozzle devices, it was found the difference between the LDFL and BOL (LDFL-BOL) increased linearly as a function of the size of the large drop. Additionally, the 2 × 2 drops formed from a lateral merging device had the same LDFL-BOL as a 2X drop formed using a single-nozzle device and an equivalent energy waveform. Table 1 has data from 9.5 μm nozzle devices; clearly the 2 × 2 LDFL is much closer to the BOL than the single-nozzle 3X large drop.

**Table 1: LDFL-BOL data from 9.5 μm nozzle devices**

| Nozzle Type | Drop Size | LDFL-BOL (μm) |
|---|---|---|
| Single Nozzle | 2X | 184 |
| Single Nozzle | 3X | 429 |
| Single Nozzle | 4X | 679 |
| lateral merging Pair | 2 × 2 | 186 |

Using the same experimental setup as above, the quality of the lateral merging drop formation was assessed for a variety of devices and waveforms. As indicated above, all testing was done using only the inside heater pair. The lateral merging drop formation quality can be described by a quality factor that is related to the expected number of drops for a given waveform. Images were captured for each condition and processed as shown Figure 7 a). The Normalized Drop Value (NDV) was calculated by dividing the actual drop count in the test image by the expected drop count. When NDV is equal to 1, then drop formation is good. An NDV greater than 1 indicates that some of the 2 × 2 drops have failed to merge, while an NDV less than 1 indicates there is unwanted merging of some of the 1X drops.

Figure 7 b) shows an example of mapping the drop formation window as a function of energy for a 9 μm nozzle pair at 2.33* $D_{Nozzle}$ spacing using a representative waveform (measured 2 mm from the nozzle plate). As shown, when there is too little energy, there is unwanted small drop merging, while too much energy causes the 2X drops to be deflected too much and there is failure to merge into 2 × 2 drops. The dashed vertical lines on Figure 7 b) indicate the operating window where both small drops and large drops can be formed. This behavior is representative of all of the lateral merging devices tested.

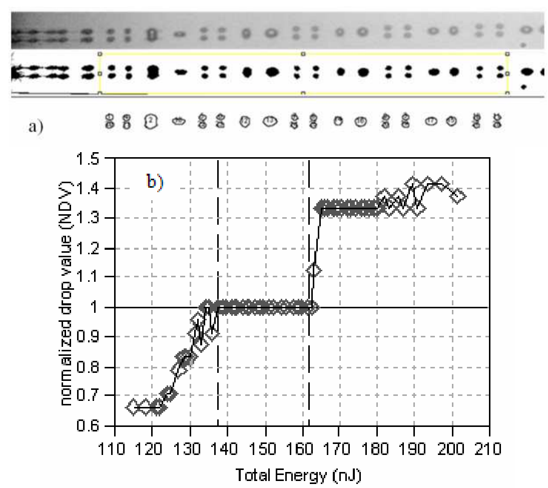



***Figure 7.*** *Image processing sequence for NDV calculation is shown in a); representative drop formation window for a 9 μm nozzle pair is shown in b).*

For a given nozzle diameter, when the energy applied is within the operating window, the operating energy input and the angle between the two jets depend on the spacing between the two nozzles in the nozzle pair. As the nozzle spacing decreases, the operating energy input increases and the angle between the two jets systematically changes from converging to diverging. Additionally, for a given geometry ($D_{Nozzle}$ and spacing), increasing the operating energy input also increases the angle between the two jets. Figure 8 shows representative data taken for 9 μm nozzles with various nozzle spacing. The distances between small drops from the two nozzles were measured at two different locations from the nozzle plate. The change in the separation of the small drops between the two locations gives the angular relationship between the two jets. Jets are parallel when distance between pairs of small drops does not depend on distance from the nozzle plate. The data clearly shows that the angle between the two jets depends on energy input to the heaters and the nozzle spacing.

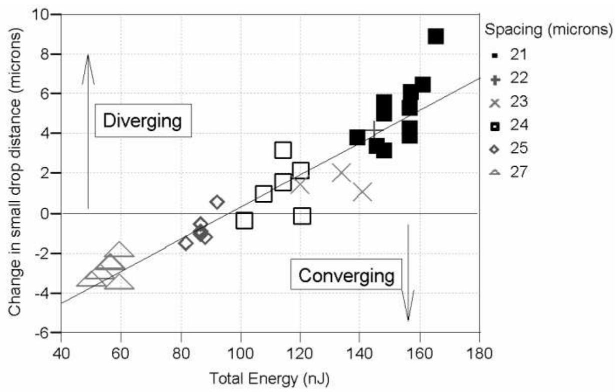



***Figure 8.*** *Convergence and divergence of small drops depending on energy and nozzle spacing.*

Once conditions were determined for drop formation, a number of print patterns were created to demonstrate that different patterns could be created using the same basic waveform and energy. Figure 9 shows some representative drop patterns formed with a single lateral merging nozzle pair.

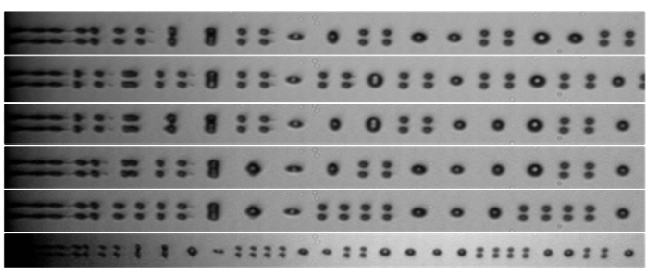


***Figure 9.*** *Images of various drop patterns made with a single lateral merging device.*

## Conclusions

In summary, dual nozzle lateral merging CIJ devices with split heaters were successfully fabricated using MEMS processes. As expected, the lateral merging CIJ devices have significantly shorter large drop formation lengths than existing single-nozzle CIJ technology. The lateral merging CIJ devices were used to clearly demonstrate the feasibility of generating patterns of small drops and laterally merged 2 × 2 large drops from the nozzle pairs. For the conditions studied, it was found that stimulating the jets with a single pair of heaters located between the nozzle pairs was sufficient for stable drop formation and discrimination between the 2 × 2 drops and the fundamental drops. Furthermore, the ability to optimize the operating window for good drop formation with energy, waveform, and nozzle configurations was presented. Within an operating window of good drop formation, it is further possible to select the energy, waveform, and nozzle spacing such that the small drop pairs deviate as a function of distance from the nozzle, reducing the likelihood of small drop merge events.

## Acknowledgments

The authors thank the staff of Kodak's ISD fabrication facility for building the polysilicon heaters, and the staff of the microfabrication and micropackaging laboratory within the Kodak Research Laboratories for their contributions on device fabrication and packaging. The authors are grateful for the device characterization work carried out by Lan Thai.

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## Author Biographies

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