Novel Silicon-Based Continuous Inkjet Printhead Employing Asymmetric Heating Deflection Means

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Abstract

In this paper, a novel continuous inkjet technology will be presented. The technology presented uses a pulsed application of asymmetric heat to a pressurized stream of ink emitted from a nozzle both to break up the stream into regularly sized printing drops and to deflect the drops onto a receiver while allowing the non-printing drops to be captured. Depending on the nozzle geometry, fluid properties and applied pressure arrays of small drop volumes (3 picoliters) can be jetted and deflected at high velocity (10 m/s). The printhead, fabricated in silicon, is produced by MEMS processing techniques that are CMOS compatible, allowing for direct integration of circuitry. The basic device geometry and operation will be described including some experimental results.

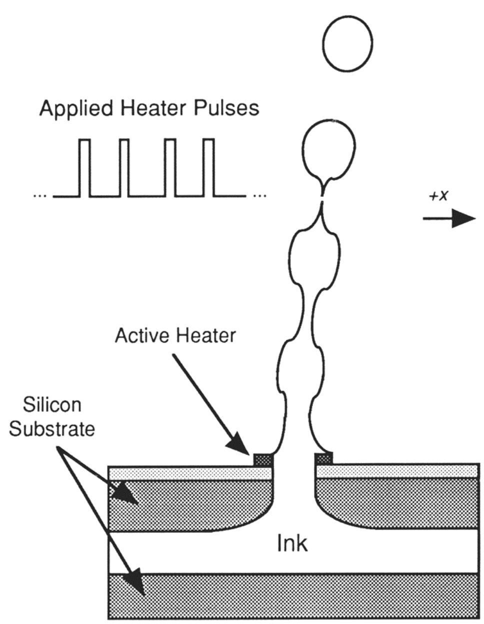

Figure 1. Schematic cross-sectional view of a nozzle

Introduction

Conventional continuous inkjet technology relies on conductive inks and electrostatic fields to charge and deflect ink droplets. Although such technology is capable of very high ink laydown rates, it is complex and costly, particularly in high image quality applications benefiting from page wide arrays. Because of the high voltages, electrostatic fields, and charged droplets, integrating an array of closely spaced nozzles with conventional CMOS circuitry is extremely difficult.

We have developed a thermally steerable continuous inkjet technology, which utilize novel mechanisms that do not rely on electrostatics for the formation and deflection of ink droplets. The printheads, described in detail in this paper, use CMOS compatible MEMS fabrication techniques, and use low energy, circumventing many of the limitations mentioned while retaining the benefits of high productivity printing with high image quality.

Principle of Operation

Figure 1 is a schematic cross-sectional view of one nozzle in operation. An ink delivery channel, along with a nozzle bore is etched in a substrate, which in this example is silicon. The ink in the delivery channel is pressurized above atmospheric pressure, and forms a stream. At a distance above nozzle bore, the stream breaks into a droplets due primarily to modulation of the surface tension by the heat supplied by the heater. The energy supplied to the heater is in the form of an electrical pulse train. To achieve synchronous drop break up only a very small amount of energy is needed (<1 nJ). The drop size may be precisely controlled by the delay time between the heater pulses, (as well as the nozzle diameter and ink flow rate, the latter of which is controlled by the applied pressure). This thermally stimulated Raleigh break up has been described in more detail by Furlani, et al.[1]

The heater is separated from the substrate by thermal and electrical insulating layers to minimize heat loss to the substrate. The nozzle bore may be etched allowing the nozzle exit orifice to be defined by insulating layers. Details of the fabrication process are discussed in a subsequent section.

Figure 2 is a top view illustration of a nozzle fabricated in silicon. This nozzle may be integrated with others to form an array of nozzles. For each nozzle, the heater has two sections, each covering approximately one-half of the nozzle perimeter. Power connections and ground connections from the drive circuitry to the heater annulus are also shown. The droplet stream may be deflected by an asymmetric application of heat by supplying electrical current to one, but not both, of the heater sections [2]. Uses for powering both heater sections will be discussed in a subsequent section. This technology is distinct from that of prior systems of electrostatic continuous stream deflection printers that rely upon deflection of charged drops previously separated from their respective streams. Heating one side of the jet causes a number of asymmetric effects to occur including lowering the viscosity of the liquid on the heated side relative to the unheated side, as well as causing a surface tension gradient along the jet-air interface on the heated side. The difference in viscosities between the two sides of the jet can lead to differences in pressure between them causing the jet to deflect from the vertical. In addition, Marangoni stress caused by an induced surface tension gradient, which acts tangentially to the fluid interface, can exert a torque that can deflect the jet away from the heated side of the nozzle. The difference in surface tensions and local curvatures on the two sides of the jet, can also contribute to the deflection.

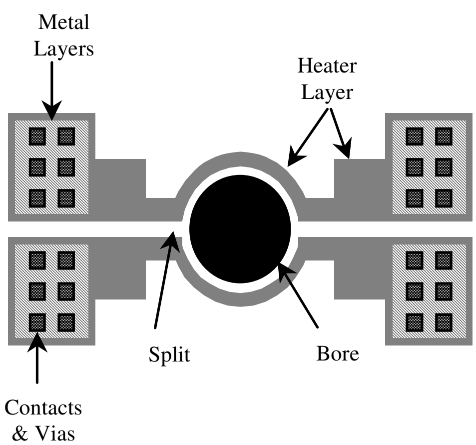

Figure 2. Top view illustration of a single nozzle

The relative importance of the aforementioned mechanisms depends on the geometry of the nozzle, the fluid being heated, and the surface properties in and around the nozzle bore. Understanding the relation of these mechanisms is an active area of research. As an example, Figure 3 shows the deflection angle dependence for two fluids (2-proponal and water) as a function of the energy per pulse supplied to one of the sections of the heater. The deflection angle denoted by θ is the angle formed between a line connecting the deflected drops to the center of the nozzle bore in the printhead and a line normal to the plane of the printhead and through the middle of the same nozzle bore as illustrated in Fig. 1. The electrical energy was in the form of a series of 1.2 microsecond pulses separated by 6.7 microseconds in time. Pressure (20 p.-s.-i.) was applied to an ink reservoir that fed the ink channel in back of a printhead having a 14.8-micron diameter nozzle opening resulting in drop velocities of 12 m/s near the printhead surface. Note the marked difference in the deflection angle dependence for the two fluids. As can be seen from the figure, 2-proponal obtains much larger deflection angles when compared to water. The deflection angle of water may be increased by the addition of such humectants as diethylene glycol (commonly found in aqueous-based inks). This dependence is discussed in greater detail in a companion presentation.

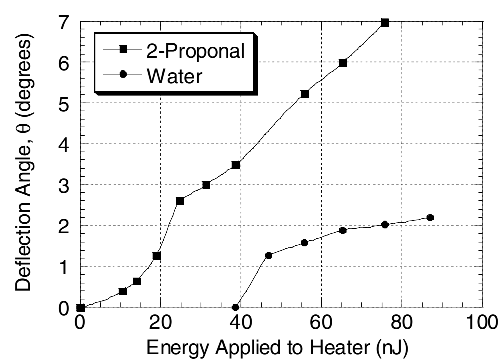

Figure 3. Plot of deflection angle versus energy applied to the heater segment

With the stream being deflected, drops may be blocked from reaching the recording medium by a cut-off device such as an ink gutter (see Fig. 1). In an alternate printing scheme, the ink gutter may be placed to block undeflected drops so that deflected drops will be allowed to reach recording medium.

Single-Drop and Multi-Drop Selection

For high image quality, high-speed printing, it is desirable to have a fast deflection response coupled with the ability to easily select one or more drops (multilevel printing). Figure 4(a) is an experimental image of a single jet producing a deflected 5-drop burst (the first two drops have merged) traveling from right to left of the figure such that it will eventually clear the top of a gutter also seen in the figure. The fluid used for this image was 2-proponal. The nozzle diameter was 8.8 microns with a drop size of approximately 3.5 picoliters. The droplets were traveling at an average speed of 9.5 m/s. The drop size may be varied by changing the delay time between heater pulses or by changing the applied pressure. The drive waveform (applied to one side of the heater) used to produce this 5 level droplet burst is illustrated in Fig. 4(b). Note that 6 electrical pulses are used to produce 5 drops. Because the deflection angle is roughly proportional to the applied energy (in the energy range used for printing) and the heater temperature is approximately proportional to the applied energy, the droplet deflection will follow the thermal envelope of the heater. This means that in the time of the first few droplet periods the heater temperature has not reached its quasi-equilibrium value resulting in these first few drops not obtaining the same deflection amount as the subsequent drops. This condition could result in drop misplacement, or depending on the gutter position, the droplets may be blocked from reaching the receiver.

A simple means to correct this condition can be seen in the applied waveform of Fig. 4(b) where the initial first few pulses have longer widths and hence are supplying more energy than the subsequent pulses. Both the pulse width and pulse delay may be varied. In addition, the pulse amplitude may be varied alone or in combination with the other factors to achieve the same means, though it is desirable from the CMOS drive circuit design to operate at a fixed amplitude.

Similarly, at the end of the multilevel drop burst the heater will take a finite time to cool resulting in fluid that forms into droplets that may have a trajectory somewhere between the non-deflected or “off” state and the deflecting or “on” state [see Fig. 4(a)]. Again, this is undesired and a simple means may be employed to correct it. A single pulse waveform as shown in Fig. 4(d) may be applied to the opposite side heater element at a fixed time after the last deflecting pulse has been issued. This results in the inter-posing fluid to actually deflect in the opposite direction into the gutter. This can be seen, after careful inspection, in the droplet stream following the last deflected drop in Fig. 4(c).

Multi-Nozzle Fabrication

The thermally steered continuous inkjet technology presented in this paper allows for close-packed integration of nozzles in silicon consistent with CMOS processes. As an example, Fig. 5 is an image of a series of nozzles fabricated in silicon; each nozzle spaced at 600 nozzles per inch (NPI). The heater surrounding the nozzle is separated from substrate by an oxynitride layer. The heater, which has a nominal width of 1 micron, was made of doped polysilicon. The 10.4 micron diameter nozzle is formed by a dry plasma etch step in the oxynitride allowing the nozzle exit orifice to be defined by this layer. The ink delivery channel and nozzle bore was formed by using deep reactive ion etching (DRIE), where the oxynitride layer can be used as an etch stop. Aluminum interconnects are used to connect the heater with the bond pads. The layers in contact with the ink can be passivated with a thin film layer for protection.

Figure 6 is an experimental image taken using the above described 600 NPI printhead. There are a total of 64 nozzles formed in a row. All the nozzles are being driven with an electrical waveform consisting of a seven pulse burst of 1.5 microsecond pulses spaced by 6 microseconds; this burst being repeated at a 100 microsecond interval. This is a demonstration of a 6-drop level burst repeated at a burst rate of 10 KHz. To reduce adjacency, effects adjacent nozzles are delayed by one-half a burst period or 50 microseconds. Though it cannot be seen in this view, the drops are actually deflecting out of the image plane demonstrating the high density, high-speed capability of the technology.

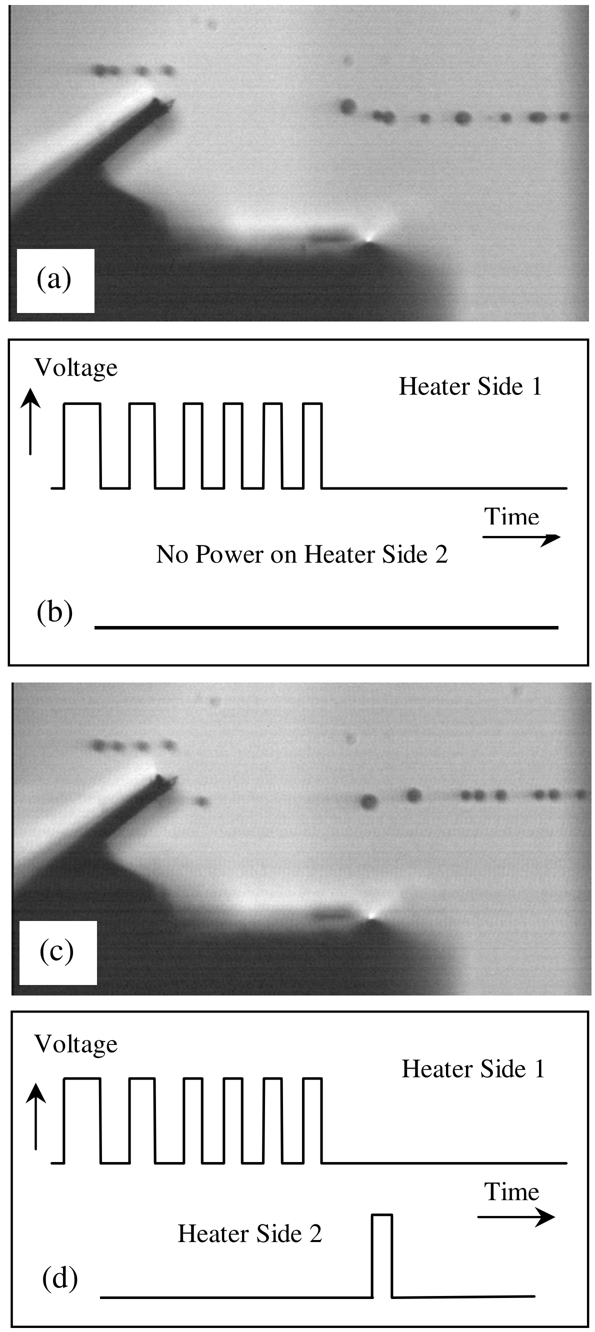

Figure 4. (a) Five-drop burst traveling from right to left with only first heater side powered. (b) Waveform used to create drop burs t seen in (a). (c) Five-drop burst using both heater sides. (d) Waveform used to create drop burst seen in (c).

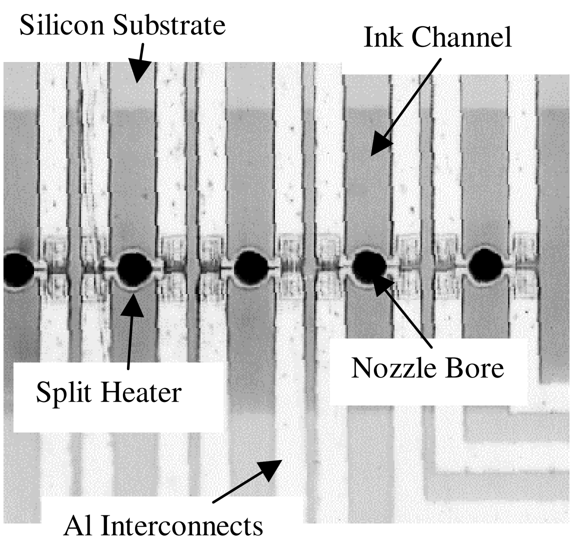

Figure 5. Top view of multi-nozzle printhead

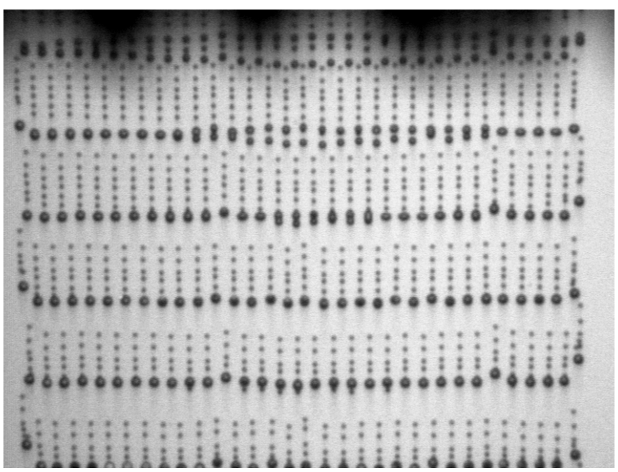

Figure 6. Experimental image of 600 NPI printhead showing 64 columns of drop bursts

Drop Trajectory Correction

By combining the ability to deflect droplets away from the nozzle side containing the active heater with the ability to control the amount of drop deflection by altering the electrical energy delivered to the heater we have demonstrated the ability to steer the droplet trajectory.[3] In addition, we have found that the deflection angle can be controlled by the length of the heater segment.[4]

Figure 7 is an example of such a nozzle containing multiple heater segments. By adjusting the power of individual segments, it is possible to steer the droplet in a 2-d plane. This technique could be useful for correcting the trajectory of an errant drop or could be used for a single nozzle enabling it to print at multiple pixel locations without moving the printhead.

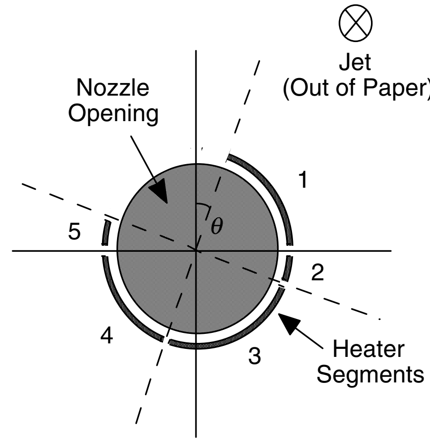

Figure 7. Top view of a nozzle having multiple heater segments used to steer drops

Conclusion

In this paper, we have presented a novel continuous inkjet technology that uses the asymmetric application of low thermal energy pulses both to break up a column of fluid into regularly sized drops as well as steer them. The simplicity of the technology as compared to conventional continuous inkjet technology combined with the CMOS integration compatibility provides a means for low cost, high density, high productivity printheads.

References

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Biography

James M. Chwalek is a senior member of the technical staff in the Research Laboratories at Eastman Kodak Company where he is currently a project leader and research scientist in MEMS technology. His interests include waveguide optoelectronics, optical thin film materials, inkjet technology, and MEMS. He received his Ph.D. in Electrical Engineering in 1991 from the University of Michigan.