The Development of a Prototype Silicon Nozzle Array for Continuous Ink Jet Printers

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Abstract

The development of a prototype, micromachined silicon nozzle array with nine orifices per colour to be used in continuous ink jet printers is described. The nozzle array was anisotropically etched in <100> silicon using the {111} stop etch planes to define the walls resulting in recessed, truncated pyramid shaped nozzles. Each nozzle is extending about 30 µm from the surrounding surface. The wall of the extending part of the nozzle is approximately 7 µm thick. To attain the desired shape the silicon wafers were subjected to three consecutive etchings. The nine nozzles within a nozzle array are connected to a flow channel, which supplies the ink. After sawing of the wafer a glass lid is anodically bonded to each silicon die to seal the flow channel. The glass lid has pre-drilled holes that fit to each end of the flow channel thereby providing in- and outlet.

A nozzle array with nine orifices (approximately 10*10µm) ejected jets at a velocity of approximately 45 m/s when a driving pressure of 18 bar was applied. The flow, for each of the nozzles, was measured to be around 0.22 ml/min. The nozzle array showed excellent droplet flight stability for all nozzles within the selected stimulation frequency range of 800 to 1200 kHz. The directivity error for the jets was measured in one dimension and the error was found to be below 4 mrad for all jets. It was possible to charge and deflect the jets individually

1 Introduction

In all droplet applications the nozzle is the key element in the unit that produces droplets. Most applications have precise demands on the size of droplets, the number of droplets that are produced per time unit and even on the deflection of droplets. In ink jet applications the crucial parameters are constant droplet size and accurate directivity of the jet. Much effort has been put into the understanding of the influence of nozzle design on droplet formation [1] for ink jet applications. [2-8]

The nozzles used today in a continuous ink jet printers are often made by glass (Siemens-Elema, Solna, Sweden)(Iris Graphics Inc., Bedford, Mass, USA). These nozzles generate one jet per colour and due to this yield long printout time. The nozzles are stimulated at a frequency around their natural droplet formation frequency to stabilise the droplet formation [1]. However, the complex mechanical construction of the nozzle unit does give rise to unwanted resonances that may interfere with the stimulation frequency. The result is that each nozzle must be tested in the manufacturing process to assure that stable droplets are produced at the desired frequencies.

Silicon nozzles have been suggested as an alternative to glass nozzles for continuous ink jet printers in several papers [9-12]. The nozzles have, however, not been fully characterised to show their ability to meet the demands of a continuous ink jet printer concerning droplet size, driving pressure, frequency behaviour and ink flow. A new nozzle design for single nozzle continuous ink jet printers was recently suggested and characterised concerning e.g. droplet flight stability [13]. This design has now been developed further to incorporate multiple nozzles for continuous ink jet printing. The shift to multiple nozzles was desired in order to substantially reduce the printout time for the continuous ink jet printer.

The suggested nozzle array design resulted in recessed, truncated pyramid shaped nozzles which were found to have excellent droplet flight stability in a large stimulation frequency range around 1 MHz for all nozzles within the array.

2 Materials and Methods

2.1 Silicon Processing

360 µm thick, p-type (boron) <100> oriented 3” silicon wafers were used as base material for the nozzle units. The nozzles were fabricated in three consecutive etch steps, see figure 1. The technique was developed to avoid the influence of wafer thickness on orifice size. A silicon dioxide layer was used to protect the areas on the wafer that was not supposed to be etched. The silicon dioxide was patterned using buffered hydrofluoric acid (HF) after lithography to uncover the wafer areas where bulk silicon etching was to take place. All silicon etching was performed using a KOH solution as etchant. The etch beaker, which contained a KOH solution (160 g KOH/500 ml H_2O), was immersed in a thermostated ultrasonic bath (Sonorex Super Digital 10P, Bandelin, Germany) to keep the etchant at a

temperature of 70°C as well as to remove gas bubbles from the wafer.

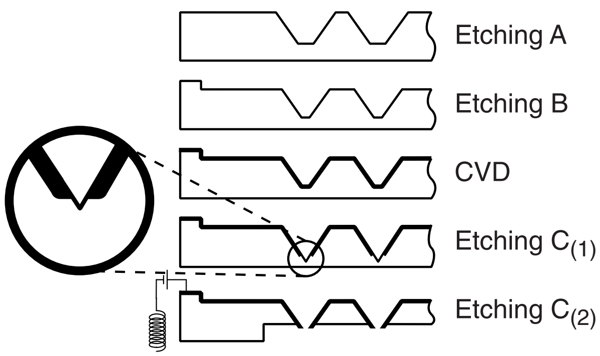

Figure 1. A schematic view of the three etchings (A, B, C) involved in the manufacturing of nozzles arrays using anisotropic and p-n junction etch stop techniques. The drawings are not to scale. (A) The depletion of silicon from a given base area resulted in truncated pyramid shaped pits. (B) The continued bulk etching of silicon shaped the flow channel and increased the depth of the pyramid shaped pits. (CVD) After etching (B) the backside of the wafer was phosphorous doped using chemical vapour deposition. (C(1)) The first phase of the third etch step was used to remove the doped silicon layer in the bottom of the pits using anisotropic etching. (C(2)) The etching was continued with the passivisation voltage [14] turned on until the nozzles were extending approximately 30 µm from the surrounding silicon surface.

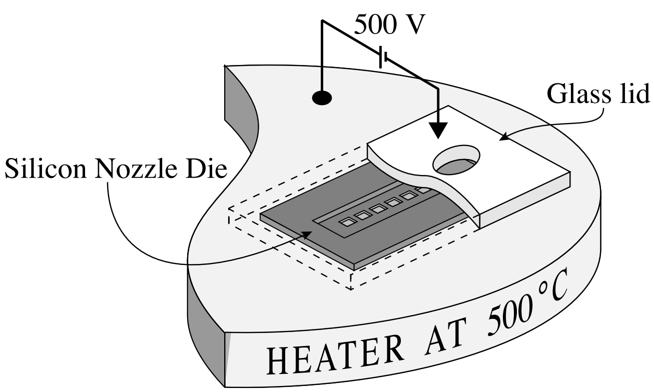

Figure 2. Anodic bonding of the silicon nozzle die and the glass lid was performed by applying approximately 500 V_{DC} over the silicon-glass junction at a temperature of approximately 500°C.

2.2 Nozzle Array Assembly

Each die was bonded [15] to a Pyrex glass-lid with pre-drilled holes that fitted to the respective ends of the flow-channel. See figures 2 and 3. The holes in the glass-lid were used as in- and outlet when supplying the flow-channel with ink.

2.3 Nozzle Array Mounting

The nozzle array was mounted in an in-house made nozzle array holder. See figure 4. The nozzle array fixture was attached to the holder with the aid of metal clips. The glass lid was larger than the silicon die so that the metal clips could hold the nozzle array firmly in place without risk of damaging the silicon die. To provide sealing between the ink channels in the holder and the in- and outlet of the nozzle array the nozzle array was fitted tight against two o-rings. To capture any large particles in the ink a 1 µm PTFE filter (Alltech, Deerfield, U.S.A.) was mounted inline inside the holder.

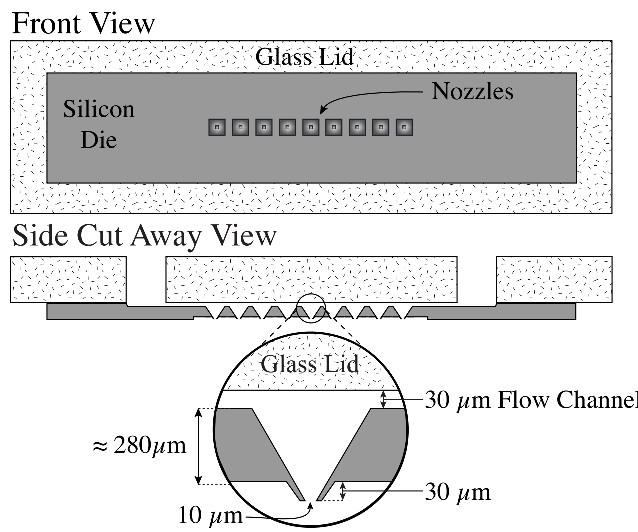

Figure 3. A cut away view of the nozzle array. The flow channel was approximately 30 µm deep and the nozzle extending from the nozzle side of the wafer had a height of approximately 30 µm. The thickness of the wafer in the flow channel section was approximately 280 µm to withstand the relatively high ink pressures used in continuous ink jet printers.

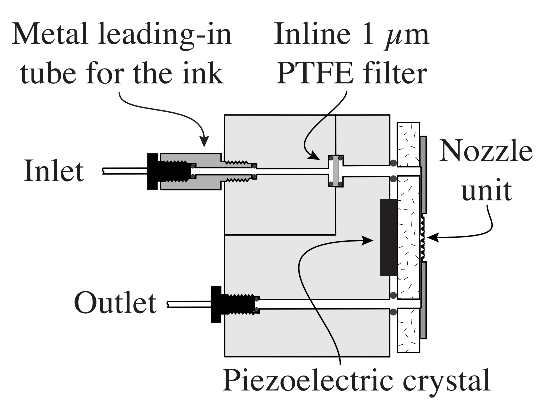

Figure 4. A cut away view of the nozzle array holder. The metal leading-in tube was used to provide electrical contact to the conductive ink in order to charge and deflect droplets. The 1 µm PTFE filter was used to prevent particles in the ink from ending up in the nozzles.

Before actual use of the nozzle array it was rinsed by flushing it through the flow-channel with Storage fluid (Siemens-Elema, Solna, Sweden), to remove debris left from the manufacturing process. See figure 5.

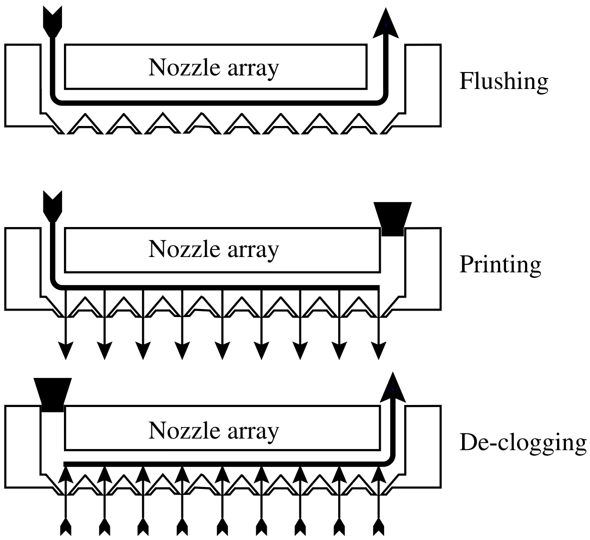

Figure 5. A schematic cut away view of the three modes of operation available with the nozzle array. ***(Flushing)*** *The initial flushing cycle where the cleaning fluid was forced through the flow channel without passing through the orifices.* ***(Printing)*** *The printing mode, where the outlet was closed with a removable seal and the ink therefore was forced out through the nozzle orifices.* ***(De-clogging)*** *The de-clogging mode where the ink was sucked out through the outlet while the inlet was temporarily closed.*

2.4 Nozzle Array Characterisation

Storage fluid (Siemens-Elema, Solna, Sweden) was used in all experiments. Storage fluid has the same physical properties as coloured ink (ρ = 1.063 g/cm3, η = 1.67 cP, γ = 48.7 dyne/cm, σ = 500 mho) but no dye is added.

The directionality of the jets is a vital parameter to measure. A deviation in directionality for a jet within the array would be observed as banding. The jets are expected to be orthogonal to the flat front surface of the nozzle array and a deviation in directionality could be measured by rotating the nozzle array around the ideal axis of the studied jet and at some distance from the orifice measure the position of the jet in the XY-plane.

A deviation in the Y-direction, orthogonal to the nozzle array and along the printlines, could easily be electrically compensated, but a large deviation in the X-direction, parallell to the array, for one or more of the jets would deteriorate the quality of the print. Therefore, a directivity error in the X-direction was most crucial to assess.

To assess the (one dimensional) directionality for the nozzle array, perpendicular to the print line, images of two adjacent jets were captured with a 1/2“ chip (756*485 pixels) CCD video camera (C5405, Hamamatsu, Japan) and the distance between the jets was measured. This was done three times for each pair of jets: close to the nozzle, at 5 mm from the nozzle and at 10 mm from the nozzle. The captured images were analysed using Matlab (The Math Works, Mass., U.S.A.) to find the centre of the jets/droplets. The distance between the orifices was measured to be the desired 500 µm with the use of a measurement device (ND 960, Heidenhain, Truenreut, Germany) connected to the microscope (BX 40, Olympus, Japan). With the knowledge of this distance it was possible to calibrate the distance per pixel without measuring the exact magnification of the microscope. The distance between two jets close to the nozzle was typically 600 pixels which corresponds to 500 µm. The resolution of the measurement system was 1 pixel which is equal to 1.2 µm.

A nozzle arrays ability to produce droplets at constant intervals was assessed by an in-house developed optical measurement setup [16]. The droplet flight stability was investigated in the frequency range of 800 kHz to 1200 kHz for each of the nozzles within a nozzle array. The driving pressure was kept at 18 bar, which resulted in an ink flow of approximately 0.22 ml/min.

The charging and deflection of unwanted droplets that is the principle of the Hertz’ continuous ink jet printer technique is complicated in the case of multiple jets. Since the jets are ejected in close proximity cross talk between the jets at the control electrode makes charging of droplets to a constant charge level more difficult [17].

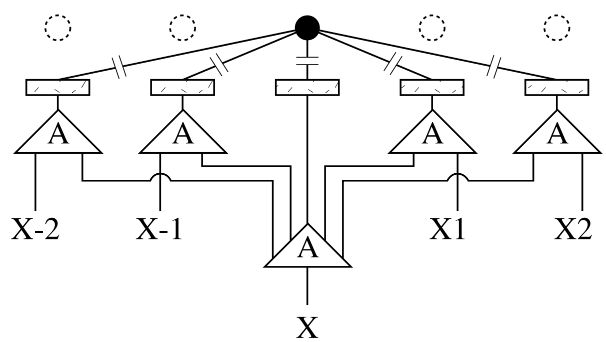

Figure 6. A compensation network [17, 18] was used to avoid capacitively coupled inter-channel cross talk. The unwanted charging influence that had to be compensated for was found to be limited to the two closest neighbouring jets in each direction (X-2, X-1, X+1 and X+2). The amplifiers, denoted by A in the figure, for each of the neighbouring channels (X-2, X-1, X+1, X+2) were supplied with a portion of the charge signal for the main channel (X) via the implemented resistive compensation network to avoid cross talk.

If one of the jets was supposed to be charged the closest neighbours would be undesirably capacitively charged. The control electrode could be designed to shield the field but such a system would be very susceptible to ink deposits. In order to assure a constant level of charge per droplet for each of the jets, without shielded control electrodes, the closest neighbours to the charged jet would have to be electrically compensated. A method to provide compensation for the two closest neighbouring jets on each side of a jet was presented by Björkengren [17, 18], see figure 6. The capacitive coupling between the control electrode for jet X and the surrounding four jets were investigated by measuring charging current for each of the jets. A fine wire mounted on a micrometer stage facilitated the selection of one of the jets. The current formed by the impact of multiple charged droplets from one jet onto the wire was measured by connecting a picoamperemeter (Keithly 485, Cleveland, Ohio, U.S.A.) between the wire and the grounded ink reservoir. This relationship was used as input for an iterative computer program developed by Björkengren [17, 18] to calculate the compensation table for the charge electrodes. The compensation table was implemented with resistors in the control electronics. Since it should be possible to charge droplets in individual jets without charging droplets in the closest neighbouring jets it was essential to measure attained charge for droplets in an intentionally uncharged jet. The attained charge should be as close to zero as possible.

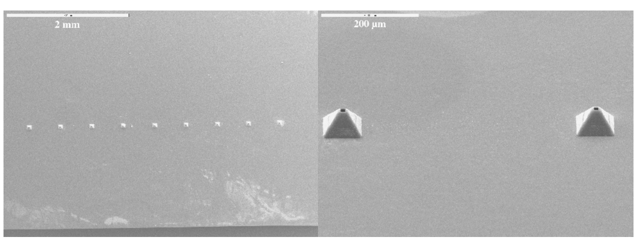

*Figure 7. **(Left)** A SEM micrograph showing an overview of the nine nozzles in a nozzle array using 25X magnification **(Right)** A SEM micrograph showing two adjacent nozzles, with uniformly sized orifices (10*10 µm), from the nozzle array shown at the top. The image to the left was captured with the nozzle array tilted 60° and the image to the right was captured with the nozzle array tilted 15°. The distance between the nozzles was 500 µm. Magnification 200X.*

3. Results and Discussion

Nozzle arrays have been manufactured and characterised with the suggested methods. The etching of the nozzles was done with anisotropic etching and pn-junction etch stop etching [14] to attain uniform nozzle size within each nozzle array independent of wafer thickness variations. See figure 7.

The manufactured nozzles had small front areas, thereby reducing the risk of deposits sticking and disturbing directivity. The pn-junction etch stop technique [14] utilised in the manufacturing produced nozzles with no sharp edges on the outside. The chamfered orifice can be studied in e.g. the SEM micrographs to the right in figure 8. When observed in an optical microscope the chamfered orifice was observed as the white frame around the orifice as shown in figure 9.

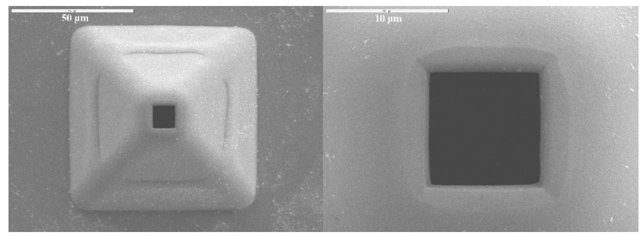

Figure 8. SEM micrographs of a nozzle with a 10 by 10 µm orifice. The nozzle can be found to the right in figure 7. The image to the right shows a view of the nozzle with a magnification of 1000X. The image to the right shows a close up of the orifice of the nozzle in magnification 5000X.

The orifice area for each of the nozzles within an array was studied to determine the size variation. The nozzle orifices shown in figure 9 were found to have a mean value of 93 µm2 and the orifice area variation within the array was calculated to be ± 15 % around the mean value The mean length of the orifice sides was 9.7 µm and the variation within the array was approximately ± 2 µm around the calculated mean.

Figure 9. A montage of micrographs of nozzle orifices captured with the aid of an optical microscope. The actual distance between two adjacent nozzles was 500 µm. The white frame surrounding the orifices was due to the illumination light that was reflected in the chamfered edge (sizes in µm).

The droplet volume was calculated for each of the nozzles and the mean droplet volume was found to be 4.0 pl for the studied nozzle array. The variation in droplet volume around the calculated mean was found to be ± 7%.

Droplet flight stability was measured for each of the nozzles within an array. If the nozzle array should operate properly it was essential that all nozzles within the array showed sufficiently high droplet flight stability for a given frequency. A droplet flight stability better than 15° (of the

360° droplet formation period) is demanded to produce a printout without misplaced droplets [19].

Since the nozzle sizes vary slightly within the nozzle arrays the natural droplet formation frequency and the maximum droplet formation frequency will vary accordingly. The measured droplet flight stability for the nozzle array can be studied in figure 10. For all nozzles within the array it was possible to achieve high droplet flight stability (below 15°) for stimulation frequencies up to around 1100 kHz.

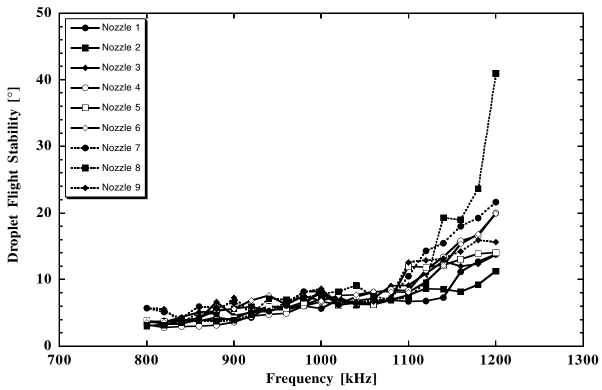

Figure 10. Droplet flight stability for the nozzle array shown in figure 9 measured at a distance of 7 mm. The measured droplet flight stability for all nozzles was measured to be below 15° in the frequency interval 800 to 1100 kHz.

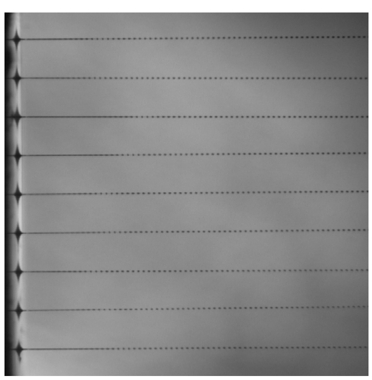

Figure 11. A micrograph of jets ejected from the nozzle array shown in figure 9. The jets are viewed in stroboscopic light when stimulated at a frequency of 1.0 MHz.

Micrographs of jets ejected from the nozzle array shown in figure 9 were captured in stroboscopic light to visualise the measured droplet flight stability within the frequency range of 800 to 1200 kHz. See figure 11. The variation in distance to the point of droplet formation that can be found in the images for the different jets were due to the varying orifice sizes and the coupling of the stimulation. The driving pressure used was 18 bar for all frequencies which resulted in a flow of approximately 0.22 ml/min for each of the nozzles.

When a droplet with a diameter of 15 µm hit the paper it did typically result in a circular dot with a diameter of 30 µm, which was the target for a droplet from another nozzle that was intended to hit the same pixel. If the centre of a succeeding droplet hit the circumference of the dot then the placement error would be 15 µm. This placement error was caused by a directionality error of 1 mrad if the paper was situated 15 mm from the orifice of the nozzle. If the directionality error was 2 mrad the entire droplet would hit the paper outside the previous dot. A directionality error of 6.67 mrad caused the droplet to hit the neighbouring line in a 10 lines per mm printer (254 dpi). In order to produce high quality prints the directionality error should not exceed 1 mrad since the eye is very sensitive to banding.

The directionality of the jets was measured length-wise across the nozzles since this was the most crucial dimension concerning print quality. The directionality was investigated for the nozzle array shown in figure 9. A micrograph of the jets ejected from the nozzle array can be studied in figure 11. The jets ejected from the nozzle array were found to have directionality errors between 0.5 and 4 mrad.

The directionality error for the jets was found to be acceptable for most nozzles within the prototype nozzle array (below 1 mrad). However, for some of the jets the directionality error was too large to be acceptable in a high quality printer (more than 1 mrad).

Another interesting parameter for the nozzle arrays was their ability to eject a jet in the same direction after repeated starts and stops. A jet/droplet pair in a nozzle array was studied with the suggested (one-dimensional) directionality error measurement method during 10 consecutive starts and stops. The time between stop and start was approximately 1 minute. The distance between the jets was measured at 10 mm from the orifices of the nozzle. The distance between the jets was found to be constant (mean 485 µm, std. dev. 4 µm) which indicated that the design has a good ability to resist the deposition of ink on the front surface of the nozzle. This was due to the rounded shape of the nozzle, which can be studied in figure 8.

The systems ability to charge and deflect droplets was visually inspected and it was observed that an individual jet could be charged without affecting the neighbours by using Björkengrens compensation method. The current was measured for neighbouring jets and it was found to be substantially reduced compared to before the compensation electronics were attached.

Conclusions

The results achieved with the prototype nozzle arrays concerning ruggedness, droplet flight stability, droplet volume and directivity for the jets within an array is promising, but further development is necessary. A reduction of the size variation within the nozzle arrays should be possible if the wafer processing is improved. It is also required to attain a reduction of the deviation error for the nozzles. All nozzles within an array should have a directivity error below 1 mrad.

The suggested method for nozzle etching showed a repeatable size reduction of 1.5 μm per dimension in the last etch step. The process is, however, not fully investigated.

The first lithography, the subsequent silicon dioxide removal and silicon etch step (A) determined the orifice sizes requiring high accuracy during these steps to attain nozzles with desired orifice sizes.

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Biography

Lars Palm received his M.Sc. degree in electrical engineering from the Lund Institute of Technology in 1993. He received his Ph.D. at the department of Electrical Measurements at Lund Institute of Technology in 1999 with a thesis on development of nozzles for the continuous ink jet technique. His primary research interests involve droplet flight stability and nozzle design. Dr. Palm has recently joined Tetra Pak Converting Technologies AB and he is a member of the IS&T. Contact E-mail: johan.nilsson@ elmat.lth.se