The Impact of Silicon MEMS on the Future of Ink Jet Printhead Design and Performance

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Abstract

Silicon Micro-Electro-Mechanical (MEMS) processing provides the foundation for a new drop-on-demand ink jet technology from Spectra, a Dimatix Division. Miniature features, piezoelectric actuators, and monolithic silicon construction create a robust platform for the development of an entirely new family of high precision printheads for a variety of printing applications. This paper will present an investigation of the performance of a 304 jet, 10 picoliter jet module, known as the Spectra™ M-300/10. Formed from single crystal silicon wafers, the M-Class jetting structure has been designed to provide very high frequency response with very low crosstalk interactions. The basic output parameters such as uniformity, straightness, and crosstalk will be analyzed. The relationships between drive pulse, drop mass, and drop velocity, which define the typical operating window for this jet module will be investigated. Opportunities to expand the operating window by utilizing the flexibility of the jet and electronics package to create larger drops will be presented. By packaging the M-300/10 in a variety of configurations, many operating scenarios can be realized.

Introduction

Drop-on-demand non-impact printing is expanding beyond conventional printing and graphics arts into applications that require increased print resolution, higher productivity, and more capable inks. As a consequence, the demands on ink jet printheads include higher operating frequencies, greater uniformity, more precise drop placement accuracy, and improved chemical resistance. Silicon MEMS processing is ideally suited for this enlarged application space, through further miniaturization of digital printing devices with increased precision and uniformity, and the utilization of inherently robust construction materials. The Spectra™ M-Class jet module is the first industrial piezoelectric printhead to fully exploit the potential of Silicon MEMS processing for emerging drop-on-demand non-impact printing applications.

The construction of the M-Class jet module is based on silicon wafer fabrication processes with a thin layer of piezoelectric to provide the jet actuation. The basic jet design is illustrated in Figure 1. The jetting mechanism includes an ink fill passage, acoustic dampening features, a pumping chamber which is capped by the piezoelectric actuator, and a descender passage that leads to the nozzle exit. The dimensions of the jet are scaled to provide very high resonance frequencies. It is important to note the presence of a thin membrane that isolates the piezoelectric from the pumping chamber, providing superior degree of chemical resistance.

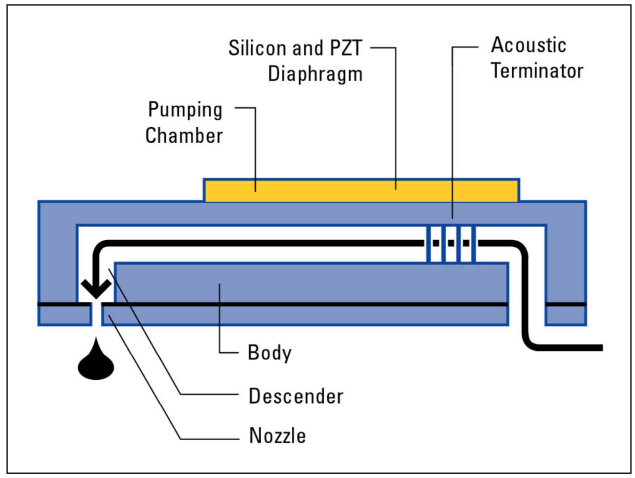

Figure 1. Schematic of basic jet design

The jets are arranged into a matrix of 304 individually addressable channels consisting of two symmetric rows. The pumping chambers are inter-digitated to provide a single row of nozzles. The nozzles are equally spaced at 0.1411 mm pitch, which corresponds to a native printing resolution of 180 dpi. A picture of the completed silicon die is shown in Figure 2. The die is about 46 mm by 6.4 mm to produce a reduced footprint that facilitates high packing densities in a large printing unit. The die is then packaged into a module assembly which includes filtration, ink inlets and electrical interconnects. These modules can then be packaged into larger assemblies, which provide native resolutions required for single pass printing or multi-color scanning applications.

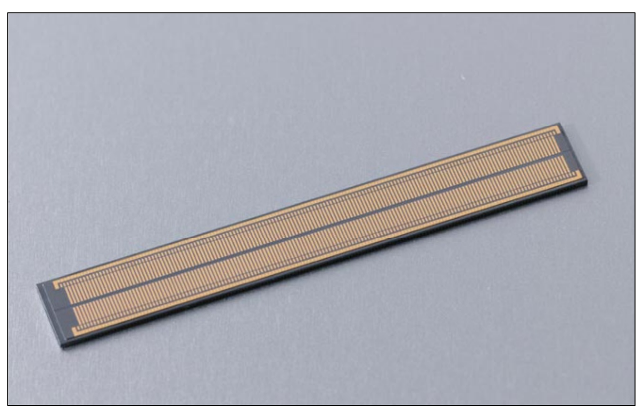

Figure 2. Layout of complete die (304 jets)

M-Class Design Characteristics

The M-Class jet module is designed to operate at voltages below 40 volts, with typical operation requiring about 25 volts. By design, module output can be varied by changing waveforms. For the purpose of characterizing the manufactured device, a nominal condition of 8 m/s with a standard waveform has been defined. In this condition with a single drive pulse, drop mass of 8 nanograms and velocity of 8 m/s are typically achieved. As voltage is increased, mass and velocity will provide the linearly proportional response shown in Figure 3. It is important to note that this response is for a fixed waveform. Other waveforms, which shift the mass/velocity relationship, will be discussed later in this paper.

The capability of the manufacturing process is evident in the performance output. For example, jet velocity uniformity is a function of the etch uniformity, wafer thickness controls, PZT fabrication and assembly techniques. Figure 4 shows the distribution of velocity over 304 jets measured at the nominal setpoint of 8 ng. The data shown has a velocity variability of 2% standard deviation from the nominal velocity of 8 m/s. This result is typical of the MEMS processing capabilities.

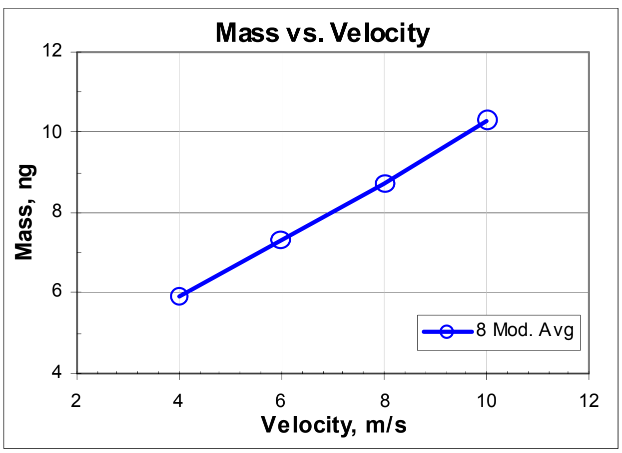

Figure 3. Mass/velocity curve for the M-Class module, shown as a function of increasing voltage for a single waveform.

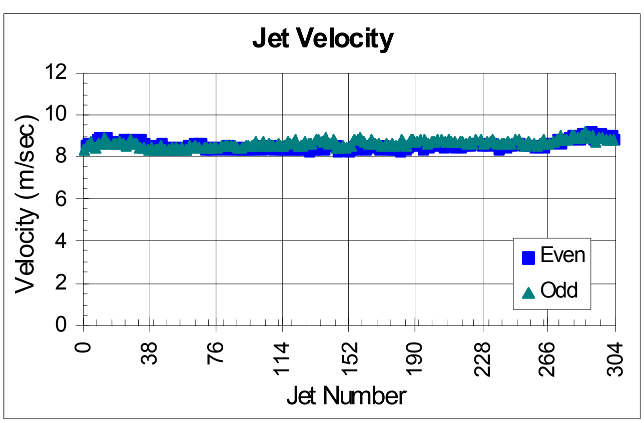

Figure 4. Velocity profile for M-Class module at the nominal test condition.

Also inherent to this design is the ability to address multiple channels with minimal interaction. This interaction, which is known as crosstalk, can be manifested as the result of a physical interaction between nearby channels. Crosstalk can serve to increase or decrease channel output as larger numbers of jets are utilized. If crosstalk between channels is more than a few percent, the uniformity of output will be negatively impacted. Imaging defects associated with crosstalk can include light and dark banding, as the drop volumes deviate from their nominal setpoint. Crosstalk is measured by firing each jet by itself and measuring drop velocity. Then each jet is fired in combination with other jets and the resulting change in velocity is measured. This delta velocity is reported as the crosstalk effect. For practical reasons, mass is not measured, but it is understood that mass crosstalk is proportional to the square root of the velocity crosstalk.

The M-Class jet module is designed for very low crosstalk. Mechanical isolation of the pumping chambers and fluidic dampening features are critical features in the module design. In Figure 5, the crosstalk effect of neighboring channels (+2/-2) is shown to be 2% for 5 modules. When many jets are fired on the array, the total effect of crosstalk is about 3%. This is comparable to Spectra^{TM} Gen 2 product technology and superior to other commercially available printheads.

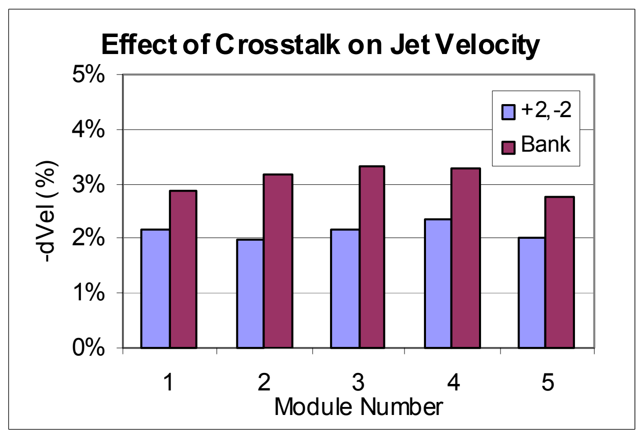

Figure 5. Crosstalk effect with neighboring jets firing and with all jets firing.

Another important outcome of the fabrication process is the nozzle straightness. Precision lithography techniques and single-crystal silicon processing allow us to manufacture nozzles with a straightness capability that exceeds any other commercially available printhead. In Figure 6, the straightness histogram of 10 printheads is shown. The data for these 10 heads is given in milliradians and the overall population has a standard deviation of 0.87 milliradians. This capability of the M-Class jet module will provide success in applications where precision is the driving requirement.

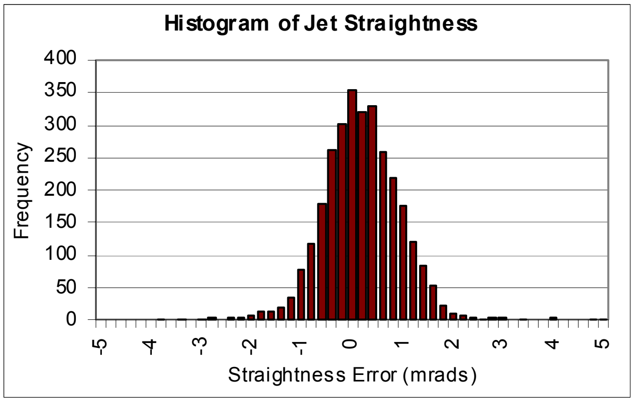

Figure 6. Histogram of jet straightness errors for 10 modules (3040 jets).

Dynamically Responsive Jet Design

For the purpose of characterizing the M-Class jet module, a nominal waveform has been defined. For this waveform, the module achieves a fixed relationship between drop mass and velocity and a fixed frequency response. The module, however, is designed to provide very high system natural frequencies on the order of 100-150 kHz. This enables the module to respond to a wide variety of complex pulses. In order to broaden the application space, waveforms can be tailored to create larger drops, faster drops or to create frequency response that targets a specific productivity window. Figure 7 shows the variation in the mass/velocity response that can be achieved by changing the waveform. For a constant velocity of 8 m/s, a range of drop mass from 8 to 16 ng is demonstrated. This is only one example of the flexibility that allows the M-Class jet module to be implemented in a wide variety of applications.

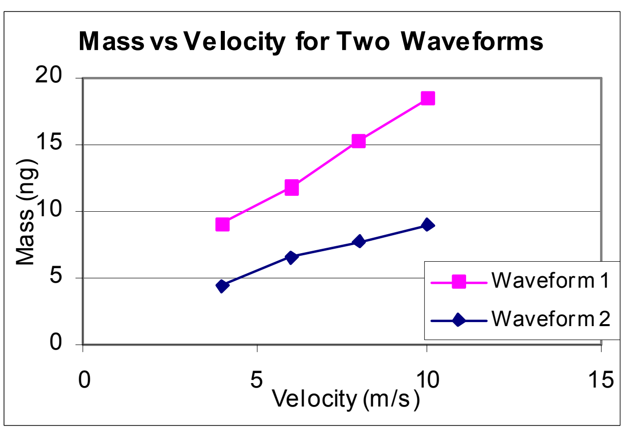

Figure 7. Mass and velocity response for variable waveforms.

Multi-Pulse / Grayscale

An important feature of new printing technologies is the ability to produce varying spot sizes on the media on a pixel-by-pixel basis. This means that each channel can eject a different amount of ink from its neighbor at each firing cycle. This process allows the end-user to maximize the productivity of lower resolution printing (large drops), while attaining the quality of higher resolution printing (small drops). There are several methods of achieving grayscale printing. The method that has been implemented in the M-Class module is to use a high frequency firing rate that produces large drops just outside the nozzle, before the drop separates from the meniscus. This is an improvement over multi-drop techniques because the flight errors of multi-drops can detract from the overall image quality.

An example of grayscale capability can be seen in Figure 8. This technique uses three different waveforms that can be stacked in a manner compatible with grayscale electronics. Each channel has the ability to be addressed with the waveform required to generate the desired drop size. In these photos, the drops emerging from the nozzle can be seen to have excellent formation properties – spherical, uniform in size and velocity, and with minimal tails or satellites. At this time, 4 level grayscale imaging has been demonstrated with the M-Class module, with small to large drop size ratios up to 5:1. The dynamically responsive nature of the jet design will enable tailored drop shaping, multi-pulse, and grayscale implementations to achieve application specific imaging requirements.

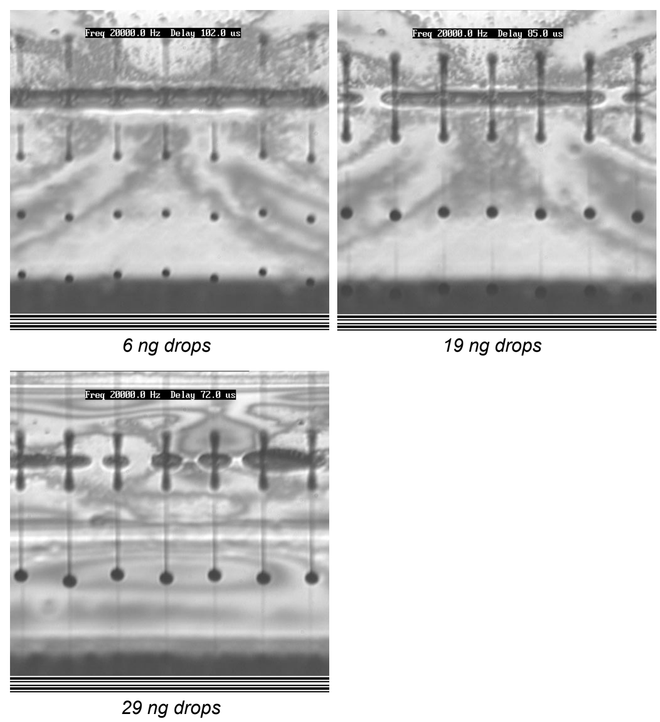

Figure 8a, b, c. Drop variation achieved using variable waveforms (6ng, 19ng, 29ng). Each waveform is a subset of the next waveform to permit grayscale operation.

Conclusion

The performance of the Spectra™ M-300/10 has been reviewed. Key design characteristics such as drop mass, drop velocity, and inherent crosstalk characteristics have been presented. The straightness capability of the silicon nozzle process has been described. In addition, the ability to use wave shaping to change the relationship between drop mass and drop velocity has been demonstrated. The ultimate reflection of this capability is shown in the achievement of 4 level grayscale, which is enabled by this technology.

The M-300/10 can be packaged into higher-level assemblies, which will provide native resolutions required for single pass printing or multi-color scanning applications. These assemblies include additional functionality such as ink supply, temperature controls and ink-level sensing. The purpose is to provide complete solutions for printing applications.

References

1. C. Menzel, P. Hoisington, and A. Bibl, MEMS Solutions for Precision Micro-Fluidic Dispensing Application, Proc. IS&T NIP20, p.169-175, (2004).

Author Biographies

Amy Brady received her BS in Ceramic Engineering from the NYS College of Ceramics at Alfred University. Amy has been employed by Spectra as an engineer since 1992. She has been involved in the development and manufacturing of many Spectra Printing Division products. Her most recent focus has been in the development of silicon micro-machining technologies for piezoelectric ink jet devices.

Marlene McDonald received her BA in Engineering Sciences from Dartmouth College and her MSME in Fluid Mechanics from the University of Massachusetts at Amherst. Since 1994, she has worked as a development engineer at Spectra Printing Division in Lebanon, NH. She has focused on computational modeling, jet design, and new product development.

Scott Theriault earned his BS in Mechanical Engineering from Worcester Polytechnic Institute and his MSME in MEMS Technology from Boston University. Scott worked for three years as a MEMS Product Engineer at Sony Semiconductor, San Antonio. He joined Spectra, Inc. in August of 2004 to focus on testing the ink jet product line which utilizes silicon and piezoelectric microfabrication.