

*Customer demands for increased performance within the precision micro-fluidic markets, including high image quality printing, can be satisfied by designing piezoelectrically actuated ink jet printhead modules with single crystal silicon Micro-Electro-Mechanical (MEMS) manufacturing processes. The result is a highly flexible design and manufacturing space. This combination allows the efficient development of a high quality product family capable of servicing a broad range of printing applications in addition to pushing "ink jet technology" into the more generalized precision liquid dispensing application space. The following text describes current performance drivers in the precision micro-fluidic and a MEMS based, bending mode, piezoelectrically actuated ink jet head, (the Spectra™ M-class) designed to meet these evolving needs. In addition, the inherent performance and manufacturing flexibility of the associated product family is highlighted.*

# MEMS Solutions for Precision Micro-Fluidic Dispensing Application

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## INTRODUCTION

Reduction in drop size is a major driver in the precision micro-fluidic markets for both printing and precision dispensing applications. Drop placement accuracy and overall jet-to-jet uniformity requirements are also expected to grow more stringent to improve quality and to allow the technology to expand into electronic materials deposition applications such as integrated circuit (IC) interconnects and display printing, ultimately leading to transistor or backplane applications. At the same time, increased printing speeds call for higher firing rates and greater overall uniformity over that operating range.

MEMS processes, a set of processes developed out of the IC industry to "sculpt" and assemble IC sized electro-mechanical structures, offer fabrication materials and processes with suitable flexibility and capability to form the platform for a product family to meet these evolving market needs. Silicon-based MEMS processing began at Bell Laboratories in the mid 1980's. Since their introduction, MEMS devices have become the standard in a variety of high volume fields including automotive sensors (accelerometers and pressure), medical pressure sensors and of course thermal ink jets. MEMS processes are capable in the <0.5µm range and produce robust, chemically resistant and reliable products.

The capability inherent in MEMS processing allows access to a new range of dimensionally scaled devices with useful performance characteristics. Furthermore, because of the flexibility of the process, new designs can be based on fluidically invariant scaling thereby leaving the complexities of the drop firing physics unchanged. Design efforts can then focus on the simplified problem involving the piezo-mechanical-acoustical aspects of the system design.

## M-CLASS MODULE DESCRIPTION

Currently, Spectra™, Inc. is developing its M-class printhead modules for high precision, printing applications. Its nominal functionality is 10-40pl drops at 8m/s. From its design and manufacture, this module will have superior straightness and minimal cross talk. In addition, the design is geared toward high firing frequencies. Pumping diaphragm natural frequencies are in the 2-3MHz range. System natural frequencies (with ink) are in the 100-150kHz range. Firing frequencies up to 40kHz are routinely achieved with the M-Class prototypes and higher firing frequencies are expected from the current design as development continues.

Furthermore, this high natural frequency facilitates ongoing development efforts of complex pulses. Spectra™, Inc. has demonstrated variable drop size and velocity-vs-firing frequency flattening with the M-class devices. Both of these features will be featured by the M-class product.

Each jet of the Spectra™, Inc. MEMS M-class head is powered by a thin piezoelectric unimorph. The unimorph is constructed in the plane of the wafer and consist of a thin PZT slab bonded to a Si diaphragm. Actuation is in the plane of the wafer. A die consists of 304 individually addressable jets that fire drops perpendicular to the wafer out of 304 in-line nozzles. Figure 1 shows the general configuration of both an individual jet, how the jets are laid-out on a die and an assembled ink jet module.

On each die 304 jets are symmetrically placed with 152 jets on each side of the die center line. All 304 nozzles are equally spaced along the centerline at a 0.2822 pitch compatible with a native 180dpi. The die has overall dimensions of approximately 45x6.5mm.

The fill paths are located along the long edges of the die. Ink flows into the device in the plane of the wafer, through a silicon filter and into a pumping chamber. Upon exiting the pumping chamber, the ink flows down a descender and out the nozzle hole perpendicular to the wafer plane.

## OVERVIEW OF MEMS PROCESSING

The major steps in the fabrication process are shown in Figure 2. The final wafer is fabricated from a three wafer stack-up: two silicon wafers and one PZT wafer. The individual die are then singulated from this wafer stack.

Silicon-on-Insulator (SOI) wafers are used twice. One forms the body of the device. The other becomes the inactive layer in the unimorph actuator. All the non-PZT processes are standard MEMS/IC processes: Metal sputtering, wafer grinding and chemical-mechanical-polishing (CMP), Deep Reactive Ion Etching (DRIE) and silicon fusion bonding. Silicon and metal planar geometries are defined through photolithography.

## PRODUCT IMPLICATIONS OF MEMS PROCESSING

A number of device level benefits immediately accrue to MEMS processed jets. To start with, Silicon, the base material for MEMS processing, is a superior mechanical material leading to a versatile product line. Furthermore, MEMS processes are statistically capable processes for the dimensions and tolerances suitable for meeting current and future ink jet technology functional needs. Lastly, design dimensions are set with masks and can be easily changed across a wide range. Together with fluidic scaling, a full product family can be efficiently designed and developed.

## ROBUSTNESS-CHEMICAL AND MECHANICAL

Silicon's material characteristics make it well suited as the mechanical material for liquid dispensing applications. In the M-class configuration, silicon plays two roles. In one role, it is simply the bulk material from which the ink jet structure is constructed. Here, silicon's resistance to chemical attack is of great value. Spectra™, Inc. has demonstrated superior resistance to a wide range of jetting formulations including aqueous inks, solvents and both highly acidic and basic fluids. Furthermore, the fusion bonds used in the processing are no less resistant to chemical attack than the bulk material. Hence, the final die stack-up has no weak spots. In addition, silicon is hard and abrasion resistant enough to allow frequent wiping and to allow jetting of abrasive suspensions.

In its other role, a thin silicon membrane is part of the driving unimorph. Here, silicon's mechanical properties are important. Silicon is relatively light and stiff, yet remains relatively tough. Silicon's strength and stiffness is important in allowing the deformations needed to generate sufficient acoustic energy to fire drops at M-class die size scales while maintaining the overall stiffness required to maintain sound speed in the pumping chamber. Furthermore, Si has a single crystal structure and hence does not exhibit creep, fatigue or deformations even over extended cycling at very high stress levels. In addition, the thermal expansion coefficient of Si is close to that of PZT. The entire unit will expand relatively uniformly and without stress under thermal loads.

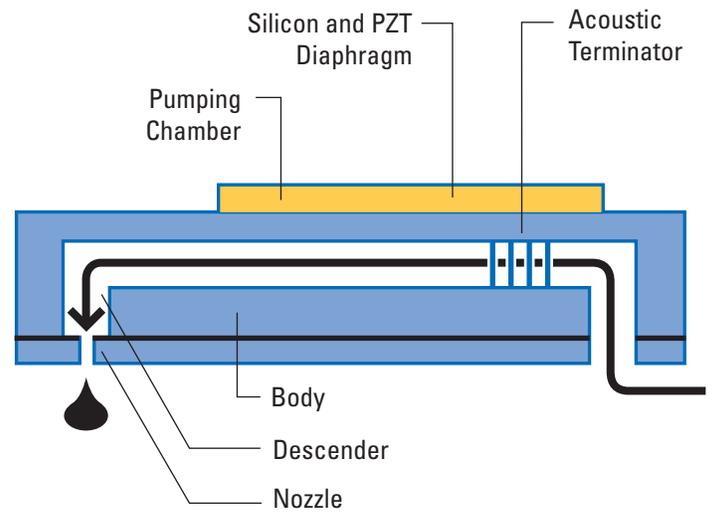


Figure 1a. Cross section of an individual jet



Figure 1b. Layout of jets on a die

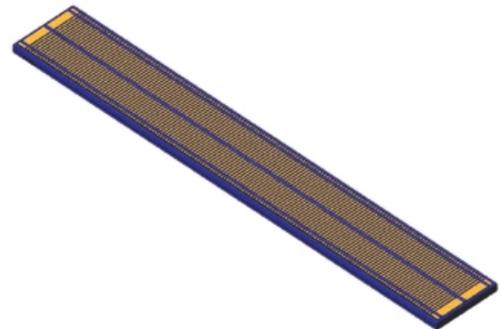


Figure 1c. Full die

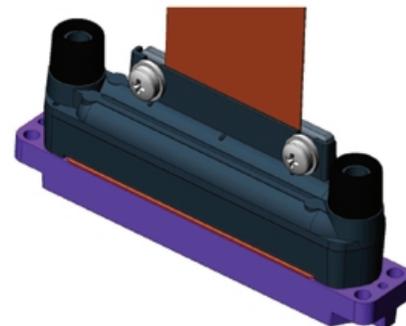


Figure 1d. Die assembled into module



Figure 2a. Starting Wafer. Begin with a Silicon-on-Oxide (SOI) Wafer.



Figure 2b. Descender/Fill etch. Etch blind holes. This *Descender* will connect the pumping chamber to the nozzle. The *Fill* connects to fluid reservoir.



Figure 2c. Pumping Chamber/Filter Etch. Etch a rectangular pumping chamber with Acoustic Terminator at fill end.

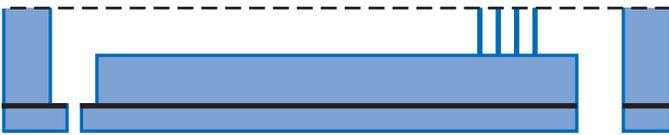


Figure 2d. Nozzle/Fill Through Etch. Etch a *through hole* to complete nozzle and fill paths.



Figure 2e. Actuator Diaphragm Attach. Attach an SOI wafer with a Fusion Bond and remove the handle wafer away to leave a (12 -50  $\mu\text{m}$ ) diaphragm.

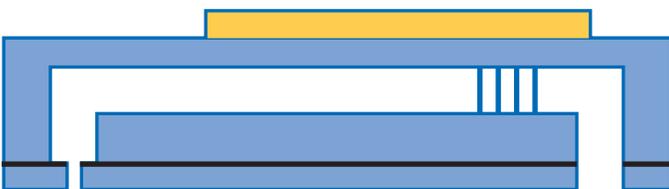


Figure 2f. PZT bond, grind and singulate. PZT, metalized on both sides is bonded to the membrane, ground to its final thickness (1- 50  $\mu\text{m}$ ) and sawn to singulate the individual jets.

## PROCESSING

The micrographs in Figure 3 show the variety and precision of MEMS DRIE processing. In the architectural approach taken with the M-class devices, the critical nozzle diameter dimension is photo-lithographically defined. Nozzle spacing distances and diameters are controlled on the sub-micron level to improve jet straightness and reduce overall drop placement error. These same gains in production repeatability are evident in all aspects of jet dimensional definition and lead to advances in jet-to-jet and die-to-die functional uniformity. Design thickness dimensions are similarly well controlled and precise, also exhibiting 1/2 micron capability. Again, this dimensional control improves jet-to-jet and die-to-die functional uniformity.

Importantly, the photo-lithographic processes and thickness processes are also extremely flexible. Different product with different jet dimensions such as nozzle dimensions, jet packing densities and jets-per-die can be produced by running the existing, developed, process with new mask sets defining the dimensions of interest. Similarly, devices with different thickness dimensions can be produced over a wide range by simply setting different target dimensions.

Taken as a whole, the drop placement accuracy of the M-class product will open up new potential for ink jet technology. Drop straightness will no longer be the limiting factor in ink jet printing systems. Integrators will have the option of increasing printing speeds and accuracy. Interlacing schemes can be reduced or eliminated. Individual modules will be significantly more uniform, improving module level interchangeability.

## DESIGN SCALING

As MEMS processing is a highly capable lithographically defined process, a very large design space is approachable by simply running the same process with mask sets presenting different dimensions. A simple example is provided by the nozzle. The nozzle diameter is defined photo-lithographically to a high degree of precision. Different nozzle sizes are simply made by changing the mask dimensions. Similarly, different nozzle spacings are made by packing the nozzle features differently on the mask.

The specifics of drop formation physics are complex and difficult to model. Fluidic dimensional scaling can be used as part of the product design process to reduce the complexity of the design task. It is well known that fluidic systems maintain functional similarity across dimensional scaling when the appropriate fluidic, non-dimensional numbers are maintained. The fluidic flow *similarity* achieved by fluidic scaling is the result of maintaining the relative size of the forces involved in determining the flows for different physical dimensions. That is, if the viscous, inertial, surface tension and compressibility forces are kept proportional, the flow will be similar. This approach maintains the drop formation physics even as drop sizes change. These pressure waves propagate through the fluidic chamber undergoing reflections and attenuation based on geometry and material constants, to form a spatially complex and time-varying total pressure function. Near the nozzle, this total pressure

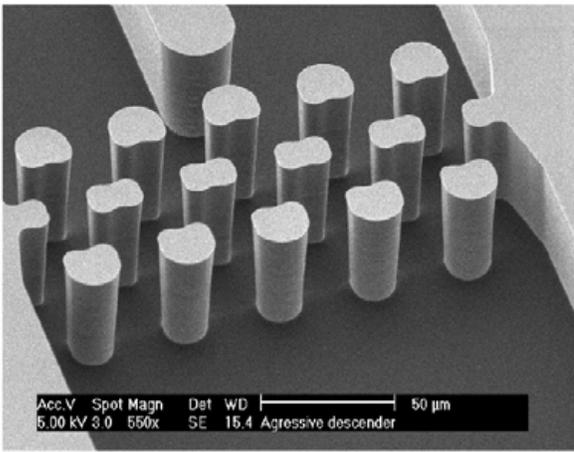


Figure 3a. Acoustic Terminator on fill side of Pumping Chamber

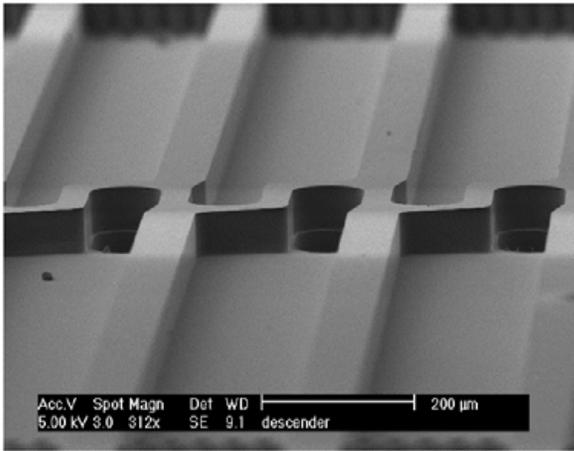


Figure 3b. View toward die center along Pumping Chamber

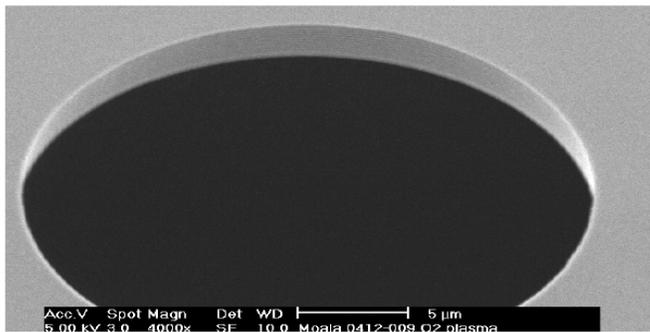


Figure 3c. Nozzle

function interacts with the other local forces (viscous and surface for example). If the pressure profile is correct, then a drop is ejected. Practically, a correct pressure profile: Invoking the fluidic scaling method discussed above leads to

- adds enough energy to overcome viscous and surface forces for a long enough time to generate flow at the nozzle,
- imparts sufficient momentum to a *drop* sized portion of fluid to give the drop velocity,
- *pulls-back* on the nascent drop sufficiently and at the correct time to cause the drop to *break-off*.

some important results. To understand these results, we will first discuss the importance of the dimensionless parameters at various points along the jet. Figure 4 shows a prototypic jet layout and identifies the important fluidic parameters at the various locations.

$$Re = \frac{\rho * U * L}{\mu}$$

$$We = \frac{\rho * U^2 * L}{\sigma}$$

In the Nozzle region, including just outside the jet where the drop is actually formed, the forces that contribute substantially to the drop formation are: pressure, viscosity, inertia and surface tension. Therefore the Reynolds number (Re) and the Weber number (We) are important.

In the Pumping Chamber and Descender Regions, the dominant forces for fluid flow are pressure and viscosity. In these regions, the Reynolds number is extremely low. The Mach number is also important in this region. The inclusion of the Mach number (Ma) as an important parameter is natural when viewed from the perspective of the function provided by the pumping chamber. As outlined above, the pumping chamber develops the pressure waves that ultimately provide the energy to create flow at the nozzle and to propel the drop.

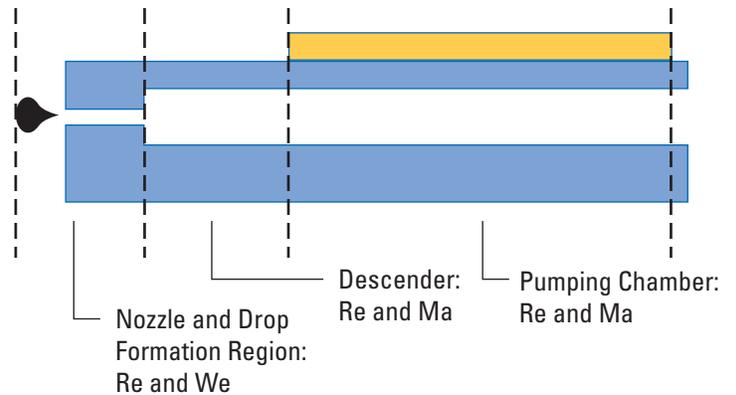


Figure 4. Important Non-Dimensional Numbers by Regions

Clearly, something to track the development of pressure is needed. Given the tie between pressure and density change, it is apparent that alternatively a number of tracking density changes or compression could be used. While Mach number is often associated with high velocity fields and as such incompatible with the very low flow observed in a jet, Mach number can be re-cast to become a description of compressibility. In fact, the introduction of the Mach number in fluids text books is often in the context of determining the significance of compressibility in derivations of the Navier-Stokes equation<sup>2,3</sup>. Therefore we see

$$Ma = \frac{U}{c} \approx \left( \frac{\Delta P}{\rho * c^2} \right)^{\frac{1}{2}} \approx \left( \frac{\Delta \rho * \rho * \beta}{\rho} \right)^{\frac{1}{2}} \approx \left( \frac{\Delta \rho}{\rho} \right)^{\frac{1}{2}}$$

that Generally, in ink jets, Mach numbers are low ( $<0.1$ ) Nonetheless, even with a very low  $Ma$ , its role in the generation of the pressure wave that drives the entire system, requires that it be taken into account. Therefore it will be retained as part of the scaling.

We are left with a number of conditions to meet to achieve fluidic similarity through a uniform dimensional scaling. Namely:

$$Re = \frac{\rho * U * L}{\mu}$$

$$We = \frac{\rho * U^2 * L}{\sigma}$$

$$Ma = \frac{U}{c}$$

all need to remain constant. Inspection shows that without changing material parameters ( $\rho$ ,  $\mu$ ,  $\sigma$  or  $c$ ), all three constants cannot remain constant. For practical applications in fact,  $\rho$ ,  $\sigma$  and  $c$  should be considered constants and solutions surrounding changes in  $Ma$  then become the focus. As an additional simplification, we have assumed that within any analysis the viscosity is constant (i.e., no localized temperature effects). The following table then outlines the impact on various functional parameters.

As noted in Table 1, under uniform dimensional scaling with an additional material freedom in viscosity, fluidic similarity can not be maintained both at the nozzle and in the pumping chamber as can be seen by the dependence of the Mach number. Hence, overall uniform scaling will lead to a new fluidic regime with unknown drop formation properties.

Table 1. Impact of Uniform Dimensional Scaling (L) Assuming Constant Density, Surface Tension and Sound Speed ( $\rho$ ,  $\sigma$  and  $c$ )

| Parameter                 | Scaling Dependence | Comments   |
|---------------------------|--------------------|--|
| Viscosity, $\mu$          | $1/L^{1/2}$        | Has solutions.   |
| Nozzle Pressure           | $1/L$              | This can get large and has implications with respect to acoustic impedance.                |
| U, drop Velocity          | $1/L$              | Since "c" will be considered a constant, this requirement indicates that $Ma$ will change. |
| Drive pulse Time Duration | $L^{3/2}$          | This parameter is related to the operational frequency of the jet.                         |
| Drop Mass or Volume       | $L^3$              | Note how quickly the drop changes size with changes in dimension.                          |

In the above analysis, the choice was made to maintain the fluidic constants in the nozzle region and force the discontinuity to the pumping chamber/descender regions. This was done intentionally with an eye towards the solution of how to design scaled jets. Experience indicates that the pressure loss associated with fluid flow across the pumping chamber/descender portions of the jet is relatively small compared to the pressure loss across the nozzle region. Hence, an approximate analysis can be completed by dividing the system into a pressure generation and delivery portion consisting of the pumping chamber and the descender and a drop formation region consisting of the nozzle as shown in Figure 5. Now, the pressure generating component can be analyzed and designed as a relatively independent voltage-to-acoustic pressure transformer if the following conditions are met:

- Pressure loss due to fluid flow in Pressure generation region is low compared to the pressure loss across the nozzle,
- Viscosity is included in calculation of acoustic losses,
- Pumping chamber and nozzle acoustic impedances are accounted for.

While this problem may indeed be complex and difficult, it represents a simplification when compared to the full fluidic problem. Importantly, the simplified problem is more tractable with existing analysis tools and methods. Further, experience shows that for the types of dimensions required for ink jets, the criteria listed above do not pose a significant obstacle.

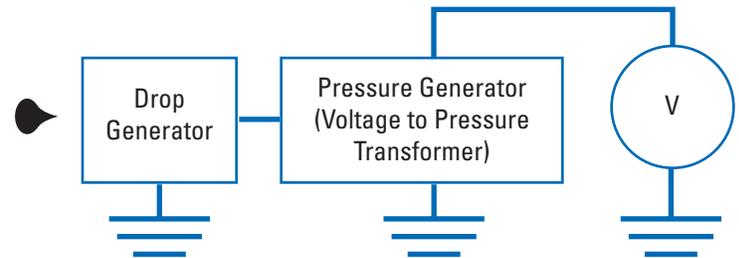


Figure 5. Simplified System

With the problem divided into two regions, scaling can be maintained independently within the regions. Now different scalings can be applied to different dimensions in the two regions to maintain functionality. Table 1 shows that the nozzle regions pressure scales as  $1/L$ . Since the acoustic wave causes this pressure, the amplitude of the pressure wave must increase by  $1/L$ . Hence, the pumping chamber must increase the pressure it generates to meet this need.

Additionally, Table 1 shows that the time scale changes. This change in time scale requires dimensional changes in both the length of the PZT along the pumping chamber direction and in the travel time of acoustic waves through the pumping chamber/descender region. This travel time scaling involves a number of factors. It must encompass the travel time for both direct and reflected acoustic waves from the nozzle side of the PZT as well as from the fill side of the PZT. Furthermore, it must comprehend the impact of pumping chamber wall compliance on the effective sound speed. This last requirement indicates that the Mach number scaling refers to the entire system: ink, chamber and chamber walls.

## MODULE FUNCTIONAL IMPLICATIONS OF SCALED DEVICES

Proceeding with the assumption that the *divided problem* is indeed tractable, Table 1 hints at the functionality that can be expected from uniform scaling of dimensions in the nozzle region. The following section looks specifically at these functionality changes and their application implications.

Perhaps the most straightforward implication is that drop sizes can be substantially reduced. This has implications within the printing market, but also has implications for the precision dispensing of electronic materials. Given the strength of the relationship between drop size and dimensions, drop sizes on the order of 10s of femto-liters and corresponding line widths on the order of <math>5\ \mu\text{m}</math> should be possible through dimensional scaling. These line widths and larger are appropriate for IC packaging application and printed circuit applications. Table 1 indicates that as the nozzle dimension drops and the drop mass decreases, the drop velocity will increase substantially. This combination is indeed a fortunate combination when viewed from the perspective of drop placement accuracy. Note that as drop velocity decreases, all other things being equal, the accuracy of drop placement goes down. Therefore it is desirable to maintain drop velocity. At small drop masses, the drop speed decreases more quickly as the drop moves away from the nozzle due to aerodynamic drag. Hence, without an attendant increase in velocity, a decrease in drop size leads either to small printing stand-off distances or to a less accurate jet. Here, we see that for uniform scaling, the increase in speed at lower drop mass will allow higher stand-off distances or greater accuracy.

Table 1 also shows that that the drive pulse time duration decreases as the dimensions decrease. This reduction in time scale is applicable to all aspects of the drop development including drop break-off and meniscus damping. Hence, successful scaling allows operating frequency to increase with the same  $L^{3/2}$  factor frequency.

The high firing rates can either be used to increase firing rates or as a powerful enabler for complex pulse schemes. Simply put, with a faster overall jet, more information can be put into a unit of time. The extra information can be used to design pulses capable of generating different sized drops from the same nozzle or to generate canceling energy to improve velocity-to-firing frequency uniformity. In this way, a faster jet opens the door for true, *on-the-fly* gray-scale printing by allowing a complex fire pulse to provide different sized drops while maintaining an overall fast firing rate.

Clearly, scaling can not continue on indefinitely. As the dimensions decrease, limitations develop. For example, the required viscosity drops as  $1/L^{1/2}$ . This requirement will begin to impose limitations on the range of jettable fluids in the 10's of femto-liter drop size where the required viscosity has dropped below  $\sim 5$  centipoise.

Further, it was noted in the pumping chamber scaling, that the chamber will need to deflect more in order to develop higher pressures. Sufficient deflection will be increasingly more difficult if nozzle dimension scaling is paired with nozzle spacing. Closer nozzle spacing implies narrower pumping chambers. Narrow pumping chambers generally lead to smaller deflections. Possible solutions are to thin the actuator in order to get larger deflections or to reduce the pumping chamber depth in order to increase the percentage volumetric change for a given deflection. Both approaches run into problems. If the actuator is thin, its compliance drops and in the face of the large pressures that need to be developed, it may not be stiff enough to maintain the sound speed or to compress the fluid. In addition, as it becomes more compliant, the sound speed in the chamber will drop. At this point, more complex scaling and design solutions may be needed. If the pumping chamber depth is reduced, the impact of viscous damping of the acoustic waves will increase thereby reducing the driving pressure. Again, more complex solutions will be needed.

Ultimately, as the nozzle dimensions drop far enough, the processing capability will require a new or different processing formula. This limit is expected to be reached for nozzles around  $3\ \mu\text{m}$  in diameter.

## CONCLUSION

MEMS processing is shown to be a powerful process for the advancement of performance parameters for precision micro-fluidic dispensing applications from printing to electronic materials deposition. Key features of MEMS processed devices are dimensional uniformity, processing flexibility and Silicon's excellent application specific properties. The processing flexibility allows easy access to a wide array of devices. Coupled with the principles of micro-fluidic scaling, this dimensional design space, permits the efficient design and development of a large range of jet dimensions with an associated wide range of performance parameters. ■

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