Applications of Ink-Jet Printing Technology to BioMEMS and Microfluidic Systems

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ABSTRACT

Applications of microfluidics and MEMS (micro-electromechanical systems) technology are emerging in many areas of biological and life sciences. Non-contact microdispensing systems for accurate, high-throughput deposition of bioactive fluids can be an enabling technology for these applications. In addition to bioactive fluid dispensing, ink-jet based microdispensing allows integration of features (electronic, photonic, sensing, structural, etc.) that are not possible, or very difficult, with traditional photolithographic-based MEMS fabrication methods.

Our single fluid and mutlifluid (MatrixJet™) piezoelectric microdispensers have been used for spot synthesis of peptides, production of microspheres to deliver drugs/biological materials, microprinting of biodegradable polymers for cell proliferation in tissue engineering requirements, and spot deposition for DNA, diagnostic immunoassay, antibody and protein arrays. We have created optical elements, sensors, and electrical interconnects by microdeposition of polymers and metal alloys. We have also demonstrated the integration of a reverse phase microcolumn within a piezoelectric dispenser for use in the fractionation of peptides for mass spectrometer analysis.

Keywords: Microdispensing, ink-jet, micro-optics, MEMS, BioMEMS, MOEMS, photonics, sensors, arrays, diagnostics

1. INTRODUCTION

The ability to manufacture smaller components and systems at high volumes, using photolithographic methods, has been at the heart of the growth in the semiconductor and electronics industries. The MEMS industry has begun to extend this success into devices that require more than electrical function. Accelerometers and pressure sensors are notable success areas. Ink-jet printers are a MEMS success area that actually predate the acronym.

Biologically active MEMS systems (BioMEMS) create significant fabrication challenges that are not easily addressed by conventional photolithographic processes. BioMEMS systems in general have more diversity of materials and function than conventional MEMS devices. Some materials (e.g., most bioactive materials) cannot hold up to exposure and/or etching processes. The thickness added or subtracted is a limiting consideration for some materials (solders, optical materials). Molecular detection involves materials and process diversity that is analogous to having a CCD (charge-coupled device) detector with each pixel made using a different process.

A solution to these problems becoming more widely accepted is the use of ink-jet printing technology to deposit materials in MEMS and BioMEMS devices. Ink-jet based deposition requires no tooling, is non-contact, and is data-driven: no masks or screens are required; the printing information is created directly from CAD information and stored digitally. Being data-driven, it is thus flexible. As an additive process with no chemical waste, it is environmentally friendly. Ink-jet printing technology can dispense spheres of fluid with diameters of 15-200µm (2pl to 5nl) at rates of 0-25,000 per second for single droplets on-demand, and up to 1MHz for continuous droplets. Piezoelectric dispensing technology is adaptable to a wide range of material dispensing applications, such as biomedical reagents, liquid metals, and optical polymers. This paper describes the use of ink-jet printing technology for a number of processes that could be applied to MEMS and BioMEMS device fabrication.

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2. BACKGROUND ON INK-JET TECHNOLOGY

Ink-jet printing technology is familiar to most people in the form of desktop office printers. Actually, there is a broad range of diverse technologies that fall into the ink-jet printing category. The physics and the methods employed within this group may differ substantially, but the end effect is repeatable generation of small droplets of fluid. Most of these methods fall into two general categories, continuous mode and demand mode, and these are discussed below.

2.1 Continuous Mode Ink-Jet Technologies

In a continuous mode ink-jet printer, pressurized fluid is forced through an orifice, typically 50-80µm in diameter, to form a liquid jet. Surface tension acts to amplify even minute variations in the jet diameter, causing the jet to break up into drops. This behavior is normally referred to as Rayleigh breakup, because of Lord Rayleigh's observations and analysis of jet breakup in the late 1800's.[1,2] If a single frequency disturbance, in the correct frequency range is applied to the jet, this disturbance will be amplified and drops of extremely repeatable size and velocity will be generated at the applied disturbance frequency. The disturbance is usually generated by an electromechanical device (e.g., a piezoelectric transducer or speaker), that creates pressure oscillations in the fluid. **Figure 1** shows a photomicrograph of a 50µm diameter jet of water issuing from a droplet generator device and breaking up into 100µm diameter droplets at 20,000 per second.
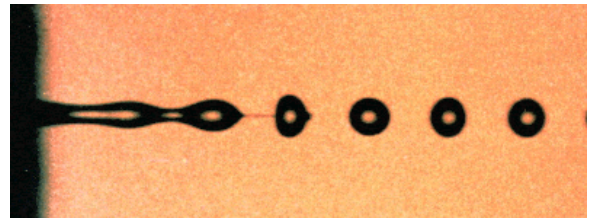

Figure 1: A 50µm jet of water breaking up due to Rayleigh instability into 100µm droplets at 20kHz.

To control the extremely uniform droplets generated by Rayleigh breakup, electrostatic forces are employed. The drops break off from the jet in the presence of an electrostatic field, referred to as the charging field, thus acquire a charge. This charge is varied by changing the voltage applied, thus supplying "data" to the drop as to its desired printing (or not printing) location. The charged drops are directed to their desired location, either the catcher or one of several locations on the substrate, by a fixed electrostatic field (the deflection field). **Figure 2** shows a schematic of this type of ink-jet printing system.

Continuous Mode Ink-Jet Technology

This type of ink-jet printing system is referred to as "continuous" because drops are continuously produced and their trajectories are varied by the amount of charge applied. Continuous mode ink-jet printing systems produce droplets that are approximately twice the orifice diameter of the droplet generator. Droplet generation rates for commercially available continuous mode ink-jet systems

Figure 2: Schematic of a continuous type ink-jet printing system.

are usually in the 80-100kHz range, but systems with operating frequencies up to 1MHz are in use. Droplet sizes can be as small as 20µm in a continuous system, but 150µm is typical. Droplets as large as 1mm (~0.5µl) have been observed.[3]

2.2 Demand Mode Ink-Jet Technologies

In a drop-on-demand ink-jet printer, the fluid is maintained at ambient pressure and a transducer is used to create a drop only when needed. The transducer creates a volumetric change in the fluid which creates pressure waves. The pressure waves travel to the orifice, are converted to fluid velocity, which results in a drop being ejected from the orifice.[4,5,6]

The transducer in demand mode ink-jet systems can be either a structure that incorporates piezoelectric materials or a thin film resistor. In the later, a current is passed through this resistor, causing the temperature to rise rapidly. The ink in contact with it is vaporized, forming a vapor bubble over the resistor.[7] This vapor bubble creates a volume displacement in the fluid in a similar manner as the electromechanical action of a piezoelectric transducer.
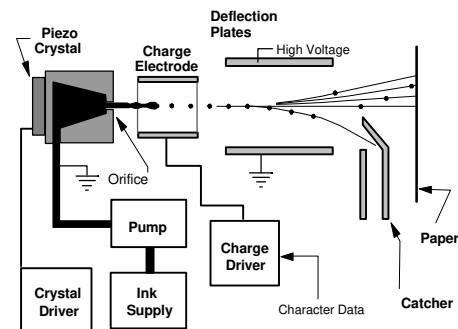
Figure 3 shows a schematic of a drop-on-demand type ink-jet system, and **Figure 4** shows an image of a drop-on-demand type ink-jet device generating 60µm diameter drops of butyl carbitol (an organic solvent) from a device with a 50µm orifice at 4,000 drops per second.

Demand mode ink-jet printing systems produce droplets that are approximately equal in diameter to the orifice diameter of the droplet generator.[8] As **Figure 3** indicates, demand mode systems are conceptually far less complex than continuous mode systems. On the other hand, demand mode droplet generation requires the transducer to deliver three or more orders of magnitude greater energy to produce a droplet, compared to continuous mode, which relies on a natural instability to amplify an initial disturbance. Droplet generation rates for commercially available demand mode ink-jet systems are usually in the 4-12kHz range. Droplets less than 20µm are used in photographic quality printers, and drop diameters up to 120µm have been demonstrated.

2.3 Discussion
As a non-contact printing process, the volumetric accuracy of ink-jet dispensing is not affected by how the fluid wets a substrate, as is the case when positive displacement or pin transfer systems "touch off" the fluid onto the substrate during the dispensing event. In addition, the fluid source cannot be contaminated by the substrate, as is the potential during pin transfer touching. Finally, the ability to free-fly the droplets of fluid over a millimeter of more allows fluids to be dispensed into wells or other substrate features (e.g., features that are created to control wetting and spreading).

Demand Mode Ink-Jet Technology

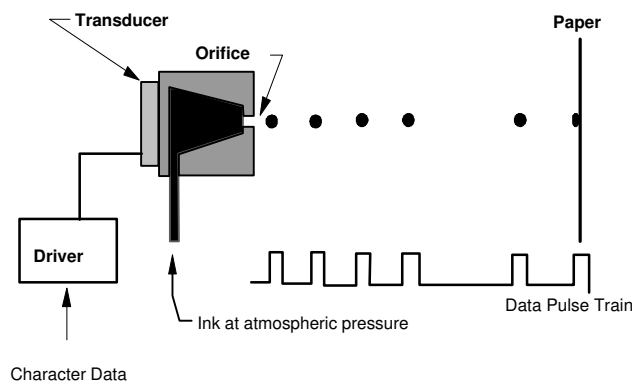*Figure 3: Schematic of a drop-on-demand ink-jet printing system*

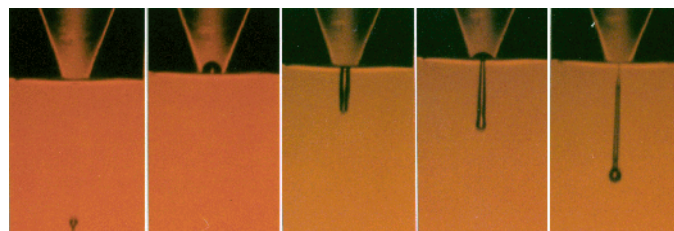*Figure 4: Drop-on-demand type ink-jet device generating 60µm diameter drops at 4kHz. Sequence from left to right spans 130µs.*

In general, piezoelectric demand mode technology can be more readily adapted to fluid microdispensing applications. Demand mode (both piezoelectric and thermal) does not require recirculation or wastage of the working fluid, as does continuous mode. It is easier to achieve small drop diameters with demand mode (again, both piezoelectric and thermal). It is easier to achieve lower drop velocities with piezoelectric demand mode. Piezoelectric demand mode does not create thermal stress on the fluid, which decreases the life of both the printhead and fluid. Piezoelectric demand mode does not depend on the thermal properties of the fluid to impart acoustic energy to the working fluid, adding an additional fluid property consideration to the problem.

2.4 Demand Mode Dispensing Device Configurations
Many drop-on-demand device configurations have been demonstrated over the past two decades. One of the earliest configurations developed is also one that is adaptable to the use of a wide range of material. In this configuration, an annular piezoelectric transducer is attached to a glass tube with an integrated orifice, as illustrated in **Figure 5**. Since glass is the only wetted material, this configuration can be used to dispense almost any material with acceptable fluid properties (<20cp Newtonian viscosity). **Figure 6** and **Figure 7** show this type of device in a housing with fluid fittings. The device in **Figure 6** is designed for high temperature operation, mainly through the selection of piezoelectric and adhesive materials, and can operate continuously at up to 240°C. It has operated for several hours at 320°C and briefly at 370°C. The devices in **Figure 7** are suitable for operation at < 100°C.

These type of devices have been used for materials as diverse as aqueous dispersion and solutions, molten solders, liquid xenon, polymers, organic solvents, and 4M salt solutions. They have been used at operating temperatures from -100°C to 370°C.

Multiple devices of the type described above may be mounted into a mechanical and hydraulic assembly to form an array. The multiple devices may be used to increase throughput or to dispense multiple fluid, as shown in **Figure 8**.

Although, it is convenient to be able to replace a single channel from an assembly, such as that shown in **Figure 8**, many of the handling and alignment issues associate with ink-jet array are simpler to address in an integrated array printhead. MicroFab has developed a family of integrated array printheads that are fabricated by sawing channels into a piezoelectric block structure.[9] The original 120 jet / single fluid configuration has been modified into 10 channel / 10 fluid, 12 channel / 12 fluid, and 16 channel / single fluid configurations for specific applications such as DNA arrays[10] and proteomics instrumentation.[11] **Figure 9** illustrates the 10 channel / 10 fluid configuration. Spacing between individual channels in this printhead is 2mm.

2.5 Demand Mode Printing System Configurations

All desktop ink-jet printers have the same configuration: the printhead is translated on one axis (nominally 100 mm/s), and the paper is indexed ninety degrees to the printhead motion. For manufacturing applications of ink-jet printing technology, the substrate to be printed upon determines the machine configuration. In most cases, the substrate will be, or will be similar to a silicon wafer, a circuit board, circuit board panel, or other flat, rigid substrate. In addition, manufacturing equipment using ink-jet dispensing will have setup, alignment, and control functions not generally found in desktop printers. **Figure 10** shows a block diagram for a typical ink-jet based dispensing system. In this case, the workpiece is shown mounted onto an X-Y stage, so that the printhead assembly is stationary. A stationary printhead does not have to be designed to account for acceleration effects on the contained fluid, or the motion of service lines if a remote reservoir is utilized. **Figure 11** shows MicroFab's jet**lab**™ research printing platform for ink-jet dispensing application development, which is based on the system configuration of **Figure 10**.
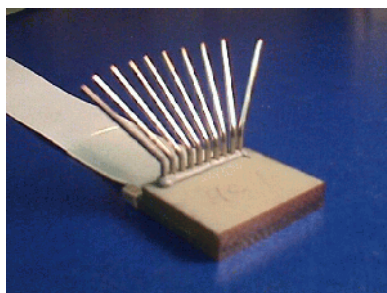

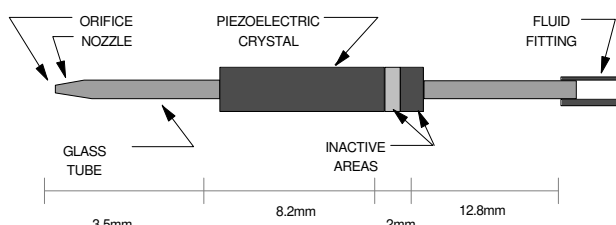*Figure 5: Single channel drop-on-demand dispensing device configuration.*

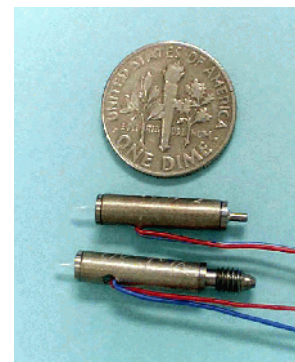*Figure 6: Single channel drop-on-demand dispensing device, T < 240°C.*

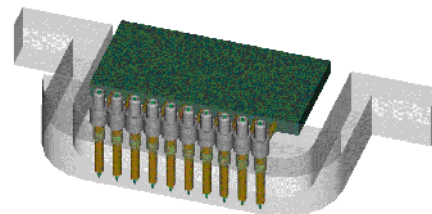*Figure 7: Single channel drop-on-demand dispensing devices, T < 100°C..*

Figure 8: Ink-jet dispenser array consisting of single channel devices mounted in a fixture.

Figure 9: 10 channel / 10 fluid integrated array ink-jet printhead.
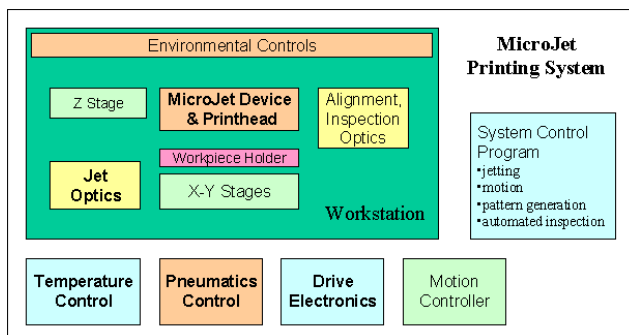

Figure 10: System configuration for an ink-jet based deposition system.

Figure 11: Printing platform for development of ink-jet dispensing applications.

3. PROTEIN and DNA DEPOSITION

Because bioactive fluids, such a proteins and DNA can be fragile and expensive, they are usually not suitable for use in photolithographic or other subtractive processes. Hence, ink-jet deposition of these materials has been of interest for almost two decades. The examples discussed below demonstrate protein deposition onto simple substrates. However, the microdispensing capabilities shown translate directly to BioMEMS configurations.

3.1 Protein Deposition

Ink-jet printing of proteins was demonstrated in the 1980's. In one application, patterns of antibodies were printed onto membranes, typically nitrocellulose, that bound the antibody for use in diagnostic assays.[12] The pattern was used as a human readable display for the assay. Examples include a prototype blood typing test shown in **Figure 12**. Here, four blood typing reagents have been printed, using demand mode ink-jet, into the characters A, B, and + (the plus contains both the control and RH positive antibodies), and have been exposed to AB+ blood. Another example is given in **Figure 13** which shows Abbott's TestPack™ product line. Here two antibodies (typically, βHCg and a control) are printed onto nitrocellulose using a two fluid continuous ink-jet printing system. In another application, piezoelectric demand mode ink jet technology was used to fabricate enzyme membranes for ISFET biosensors,[13] which can be considered early BioMEMS devices.

Figure 12: Four antibody test printed using ink-jet technology.

Figure 13: Two-antibody diagnostic assay (TestPack™) printed using ink-jet technology.

In the early 1990's, with the goals of increasing the number of diagnostic tests that could be conducted in parallel, and of increasing the sensitivity of the assay by minimizing the amount of analyte bound to the antibody,[14] Boehringer Mannheim (now Boehringer Roche) Diagnostics developed their MicroSpot™ system. As many as 196 distinct reactions sites (i.e., spots) would fit into their disposable reaction well, shown in **Figure 14**, and be imaged using a fluorescence confocal scanning microscope. The initial pilot line used ten separate ink-jet deposition stations to deposit a total of ten fluids. Each fluid was printed into multiple spots to provide redundancy, and a real-time inspections system imaged the printed dots using a secondary fluorophore. **Figure 15** illustrates the results obtained from two different immunoassays in the MicroSpot™ format.[15] Transition of each printing station from a single to ten fluid simultaneous deposition to result in a 100 fluid pilot line was underway in 1999 when the line was shut down.

Figure 14: Disposable diagnostic test that contains up to 100 tests printed using ink-jet technology.

3.2 DNA Deposition

Although the most prevalent DNA array fabrication techniques have been Affymetrix's light-activated DNA fabrication method[16] and pin transfer, ink-jet printing methods have been used by a number of organizations, both for synthesis and for deposition of oligonucleotides in a microarray format. Deposition of oligonucleotides that are synthesized and verified off-line has been accomplished by using methods such as, commercially available six color thermal ink-jet printheads;[17] conventional fluid robots that have been modified to hold 4, 8, and possibly up to 96 individual glass capillary piezoelectric demand mode jetting devices;[18] and custom piezoelectric demand mode array printheads.[10] The chief difficulty in deposition of oligonucleotides is the number of fluids to be dispensed. For very specific genetic resequencing applications (i.e., looking for known sequences or mutations), the number of oligonucleotides required can be as few as ten to less than 100. Resequencing applications include clinical diagnostics, SNP (single nucleotide polymorphism) detection, and point mutation detection. Resequencing assays fabricated using ink-jet deposition of oligonucleotides have been demonstrated for drug resistant *Mycobacterium tuberculosis (Mtb)*, as illustrated in **Figure 16**.

4. CHEMICAL SYNTHESIS

Deposition of bioactive molecules allows known, quality controlled materials to be applied to substrates. If a large number of different molecules is to be deposited, a simpler and more flexible method may be to fabricate those molecules *in situ* using ink-jet deposition of precursor materials. Oligomeric materials are most suited to this approach with DNA and peptides being obvious candidates. Although, only these two bioactive molecules are discussed below, this approach is valid for general combinatorial synthesis.[19]

4.1 DNA Synthesis

Synthesis of DNA arrays using ink-jet technology greatly decreases the number of different fluids required. Only the precursor solutions of the four constituent bases (A, G, C, T) of DNA, plus an activator (tetrazole), are jetted, as illustrated in **Figure 17**. Each "layer" of bases is synthesized with only a single activation step. This is a considerable simplification compared to light-activated synthesis of DNA arrays[16] which usually requires four activation steps per "layer." The complexity of multi-step chemical synthesis in an anhydrous environment is an added problem, but a number of investigators have overcome this difficulty.[20,21] DNA arrays manufactured in this way using ink-jet technology are available from Protogene, Agilent, Rosetta Informatics, and Oxford Gene Technologies.

4.2 Peptide Synthesis

Peptide arrays for drug and expression screening studies[22] can be synthesized using ink-jet can in a manner similar to DNA arrays, except that there are 20 naturally occurring amino acids, making the dispensing system more complex. Initial proof-of-principle peptides are currently being fabricated at MicroFab using an adapted jet**lab™** printing system.

5. BIOPOLYMER & SOLID SUPPORT APPLICATIONS

Biopolymer microdispensing has applications in tissue engineering, drug delivery, and the creation of biomolecule attachment / reaction sites. Other materials can be dispensed to create and/or modify solid support structures at very high resolution. Efforts in these areas to date have not focused on MEMS and BioMEMS configurations, but could be readily extended to them.

5.1 Tissue Engineering

The ability to "write" biopolymers, cells, and growth factors (stimulants and inhibitors) with nanoliter (and smaller) volume precision opens the possibility of digitally constructing engi-neered tissue using ink-jet printing technology. Biosorbable polymers (PLGA) can be printed as a three dimensional structure, using methods currently employed in free-form fabrication, to form scaffolds in the desired tissue shape. Cells seeded into this scaffold would grow into this shape and gradually dissolve the polymer structure after it has been
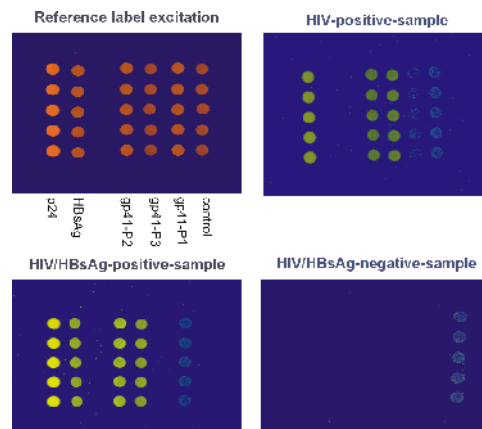

Figure 15: Immunoassay, ink-jet deposited spots ~100µm (courtesy Boehringer-Roche).
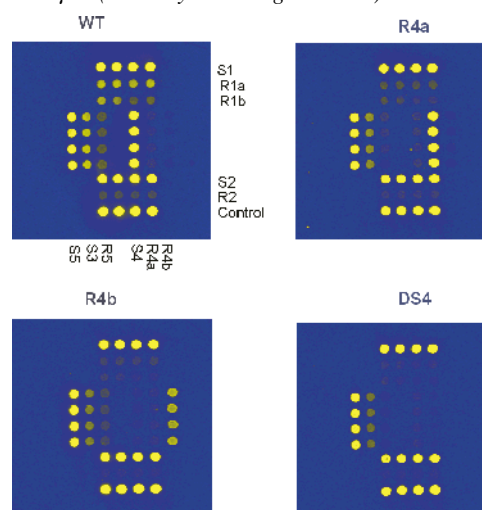

Figure 16: DNA test, drug resistant Mtb.,.ink-jet deposited spots ~100µm (courtesy Boehringer-Roche).
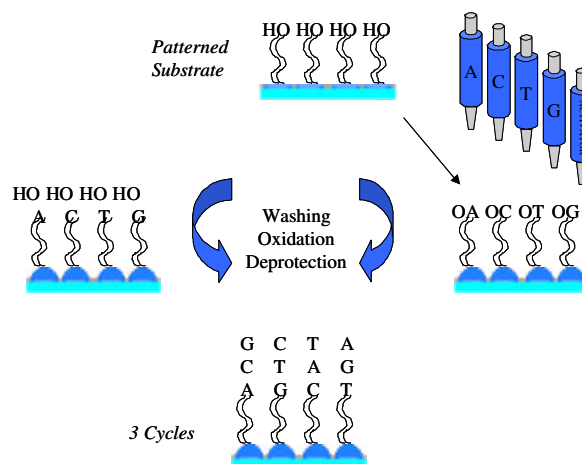

Figure 17: Schematic of ink-jet based DNA array synthesis.

implanted, leaving only the tissue and no "foreign" materials for the body to reject.

One of the primary barriers to tissue engineering is the creation of a vascular structure in tissue being grown. By selectively dispensing biopolymers, cells, and growth factors, it may be possible to create vascular structures (and nerve conduits) using ink-jet dispensing. **Figure 18** illustrates the concept of creating the polymer structures using ink-jet technology and **Figure 19** shows initial results obtained at MicroFab in creating small features from biosorbable polymers. **Figure 20** shows human liver cells being dispensed using an ink-jet device. Viability testing of the cells after they had been dispensed indicated no immediate effect as the result of the dispensing process.

Figure 18: 100μm polymer lines written with ink-jet technology.

Figure 19: PLGA lines, 275μm wide, printed using ink-jet technology.

Figure 21: 50μm spheres of cholesterol for use in controlled release of hormones.

Figure 20: Human liver cells being dispensed using an ink-jet device.

5.2 Drug Delivery

The same family of biosorbable polymers used in creating structures for tissue growth can be loaded with small molecules, steroids, proteins, peptides, genetic material, etc. to be used as therapeutic agents (i.e., drugs). Embedding these materials in the polymer allows for controlled release, with the polymer formulation and the geometry controlling the release profile. The simplest shape useful for drug delivery is spheres, which can be controlled to a very uniform diameter, or generated in a specific diameter distribution. **Figure 21** illustrates both the creation, via ink-jet technology, of microspheres for drug delivery, and the use of materials other than polymers as the delivery vehicle, in this case cholesterol.

5.3 Solid Support Creation and Modification

In an application analogous to printing polymers for tissue engineering, other materials can be printed using ink-jet technology to create or modify solid support structures to be used as attachment or synthesis sites for bioactive molecules; to locally control of wetting or reactivity; or to create a time release flow obstructions. Solid phase materials such as nitrocellulose (see **Figure 22**), methyl cellulose, sol gels, and biotinylated PLGA have been dispensed onto substrates using ink-jet technology. Chromic acid has been used to modify polypropylene and acetone to modify polystyrene (see **Figure 23**). Finally, cleavable linkers such as succinate, amidate have been dispensed.

Figure 22: 120μm spots of nitrocellulose printed on glass using ink-jet printing.

6. CHEMICAL ANALYSIS

Ink-jet systems commonly contain functions other than the dispensing function. Filtration and temperature control are common, and fluid mixing systems have also been included. For biochemical analysis, the capture, concentration, and release of molecules of interest is a common function prior to analysis, usually involving mass spectroscopy.[23] Using an ink-jet device to perform this function may make the interface to chemical analysis MEMS devices simpler and smaller.
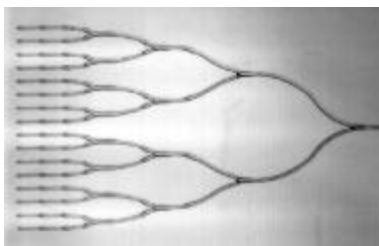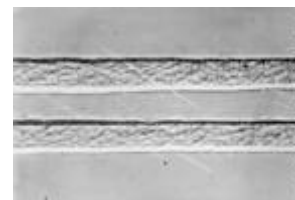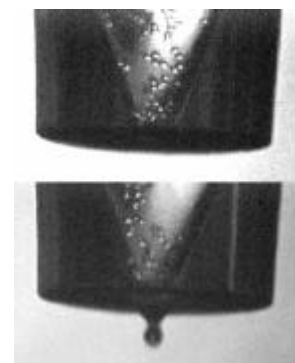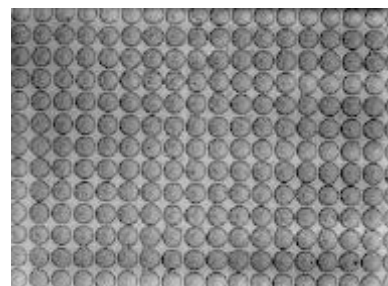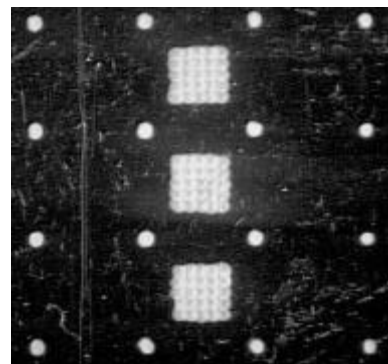

Figure 23: 0.5mm regions of polypropylene modified by ink-jet printing acetone.

MicroFab has integrated capture media into the single channel devices discussed above. One configuration is shown in **Figure 24**. The capture media in this device is C18, which is used in the capture and concentration of peptides. Other capture media (e.g., C3, C4, C8, ODS, CN, TMS, HPL, MC, phenyldiisopropyl) can be integrated into ink-jet devices. MicroFab is currently developing both low-volume and array configurations.

After a sample has been captured, solvents are used to release the sample over time resulting in a separation of parts of the sample in relationship to their affinity to the capture media (i.e., traditional liquid chromatography). The flow of solvent is caused by jetting drops from the device, and these drops can be printed on solid support. Thus, the time domain for conventional liquid chromatography (LC) can be translated into the spacial domain, allowing both archiving of the separated sample and use of MALDI-TOF (matrix-assisted laser desorption of ions - time of flight) mass spectroscopy (MS) methods. This compares to the discarding of samples and use of the more complex electrospray detection in conventional LC-MS.
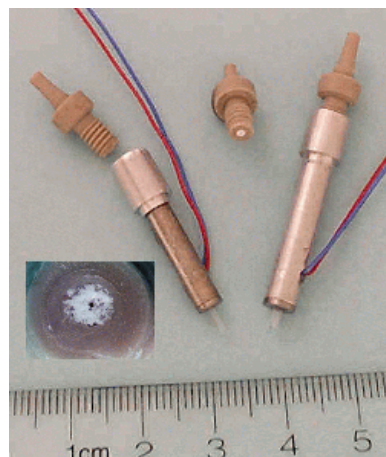

Figure 24. Ink-jet device with detachable reverse phase column (C18).

7. MICROASSEMBLY

Local addition of an electronic or photonic material, using ink-jet technology, in a MEMS or BioMEMS allows the creation of features and the use of materials that are not feasible with photolithography. In some cases, it may lower the cost / complexity of fabrication compared to photolithography. A number of examples are given below.

7.1 Electronic Materials

Solders have been dispensed using piezoelectric demand mode ink-jet technology.[24,25] Operating characteristics include: formation of spheres with diameters of 25-125µm; drop formation rates (on-demand) up to 1,000 per second; deposition onto pads at up to 600 per second; and operating temperatures to 320°C. The solder dispensed has been primarily eutectic tin-lead (63Sn/37Pb), but a number of other solders have been demonstrated, including high lead (95Pb/5Sn), no lead (96.5Sn/3.5Ag; indium; 52In/48Sn), and low temperature bismuth solders. **Figure 25** shows results from printing solder onto an 18x18 test coupon with 100µm diameter pads on 250µm centers. The deposited solder volume is equivalent to a drop diameter of 100µm. Note that the bump shape

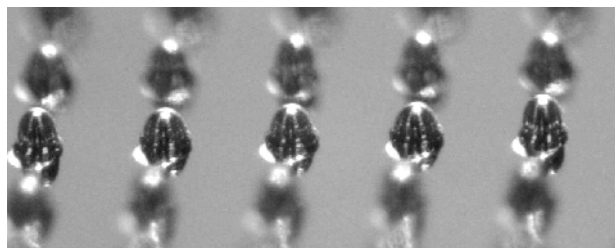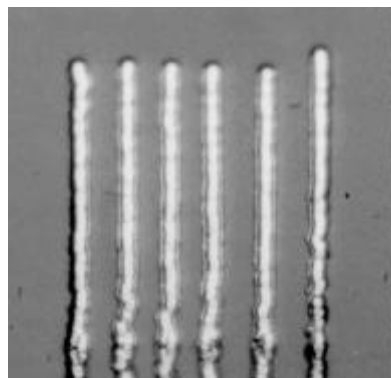*Figure 25: 100µm solder bumps ink-jet printed onto 100µm pads on 250µm centers at 400 per second.*

shown in **Figure 26** is a consequence of rapid (<100µs) solidification.[26] Multiple drops of solder can be dispensed onto a single site. If the substrate is not heated, generally the solder droplets will solidify before the impact of the next drop, pro-

Figure 26: Model [26] of jetted solder bump (left), and 80µm bump (right).

ducing a tower like object, as shown in **Figure 27**. Extension of this simple geometry into more complex shapes 3-D shapes may be possible, but will be limited by how the impacting solder drops wet the solidified drops.
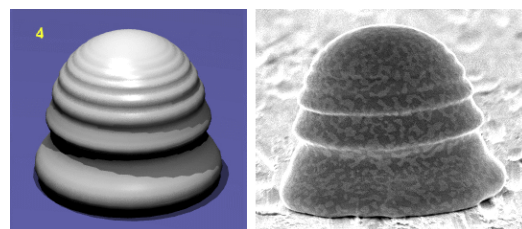

Figure 27: 25µm diameter solder towers printed on 50µm centers.

Resistive polymer solutions (aqueous and organic solvent based) have been dispensed to form imbedded resistors on the inner layers of multilayer circuit boards. **Figure 28** shows a portion of a test vehicle on a 18"x12" core sheet. Resistors ranging from 100Ω to several MΩ have been created using materials with resistivities as low as 200Ω/sq. Printed resistors can be much smaller that discrete resistors.

Dielectric layers can be applied using ink-jet technology in patterns so that they are applied only where they are needed. **Figure 29** shows a disk drive head component with UV-cure epoxy printed over 50µm wide gold leads.

Other electronic materials that have been dispensed using ink-jet technology include polyimide, organometallics, and photoresistors.

7.2 Photonic Materials
Ink-jet technology has been used to "write" refractive microlenses, and waveguides[27,28] using optical epoxies, with the key advantage that they can be fabricated directly onto optical components of arbitrary geometry.[29,30,31] Refractive microlens configurations which may be printed using ink-jet processes range from convex/plano hemispherical, hemi-elliptical and square,[32] to convex-convex. Arrays of thousands of microlenses have been ink-jet printed for use as free-space optical interconnects in VCSEL-based photonic switches,[33] with 13,872 lenslets being printed on a single wafer. **Figure 30** illustrates a section of one of these lenslet arrays. The red box indicates a VCSEL / detector pair. Hemi-elliptical and square microlense are illustrated in **Figure 31** and **Figure 32** where adjacent droplets are printed along one and two axes, respectively, and allowed to flow together prior to solidification and curing. The elliptical and square lens configuration could be useful in edge-emitting diode laser collimation and light-collection for detectors, respectfully.
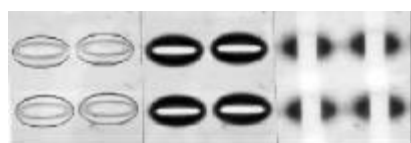

Figure 28: *Conductive polymer resistors printed using ink-jet technology, <200Ω/sq, ~1mm long.*

Figure 29: *Disk drive head component with UV-cure epoxy printed over 50µm wide gold leads.*

Figure 30: *Portion of printed array of 300µm diameter lenslets for use in "smart-pixel" based datacom switch.*

Figure 31: *Printed hemi-elliptical microlenses 284µm long; substrate, fast-focal and slow-focal planes.*

Figure 32: *Printed 300µm square microlenses; focal plane and profile.*

The process for printing multi-mode waveguides is similar to that utilized for hemi-cylindrical microlenses, except that the deposited optical material must be higher in refractive index than the target substrate. Arbitrary patterns of waveguides may be printed by utilizing software which enables precise adjustment of features such as number & location of branching points, turning radii and segment lengths, as illustrated in **Figure 18** and **Figure 33**. Edge smoothness of the guide-substrate interface is on the order of the wavelength of the transmitted light and is superior to etched waveguides. To date, waveguides have been written only with materials with unacceptably high loss, but use of low loss materials is under evaluation.
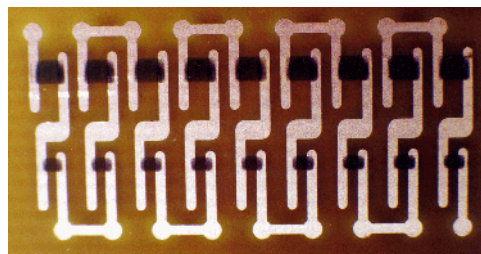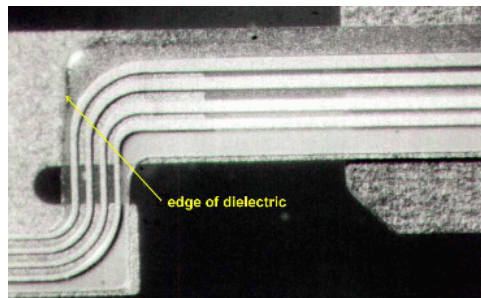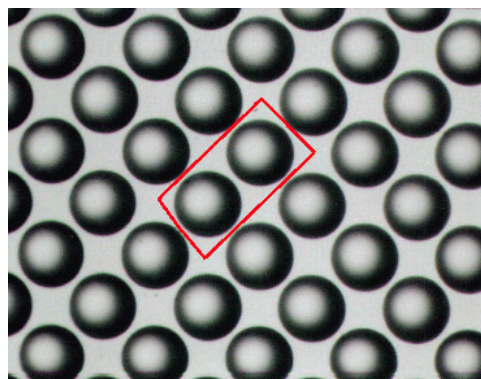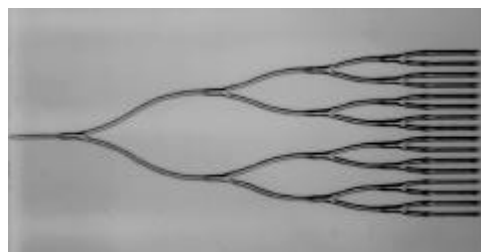

Figure 33. *25mm long, 1-to-16 branching waveguide printed using ink-jet technology.*

Chemical sensor materials can be ink-jet printed onto detectors for use in clinical diagnosis,[34] manufacturing process control, environmental monitoring, etc. UV-curing optical epoxies used can modified to be porous and doped with chemical indicators. These can then be printed as sensor array elements onto detection surfaces, such as the tips of imaging fiber bundles, providing a sensor configuration as exemplified by **Figure 34**.

Figure 34: Array of 80µm indicator elements printed onto 480µm fiber-optic bundle.

Active optical materials printed with ink-jet technology have principally been for display applications. Phosphor inks have been printed onto glass substrates as lines and arrays of spots, both with 90µm feature sizes. The SEM's of **Figure 35** and **Figure 36** illustrate the resulting patterns. These printed features are smaller than pixels currently used in many phosphor displays, and have high density and uniformity of particles in the pixels.

Light-emitting polymers are a subset of a broad class of conjugated polymers. To construct active devices with these materials, a uniform layer of approximately 1µm must be created in a structure, and the structure must create an electric field across the light-emitting polymer layer. Whether it is deposited in a spin-coating process or by ink-jet deposition, the polymer is usually suspended in low concentrations (0.5-2% by volume) in a volatile organic solvent

Figure 35: 90µm line of ink-jet printed phosphor.

Figure 36: 90µm spots of ink-jet printed phosphor.

such as xylene. After deposition, the solvent is driven off and the polymer film is left behind.[35] MicroFab has demonstrated that feature sizes as small as 35µm can be achieved when printing light-emitting polymer solutions onto a surface coated with hole-injection layer material. **Figure 37** illustrates the spot quality and resolution that can be obtained by ink-jet printing of light-emitting polymers.

Figure 37: 75µm diameter spots of light-emitting polymer (fluorescing) printed onto glass.

7.2 Other Materials

Adhesives for sealing and bonding can be ink-jet printed. Simple line (see **Figure 38**) and dot patterns can be applied. In addition, complex patterns that vary both the spatial and volume distribution of adhesive can be printed, as shown in **Figure 39**. The same materials can be used for spacer bumps for flat panel display assemblies. Bumps as small as 25µm in diameter and 10µm high have be created. **Figure 40** shows an example of printed spacer bumps that would meet the physical and thermal (in excess of 200°C) durability requirements for flat panel displays.
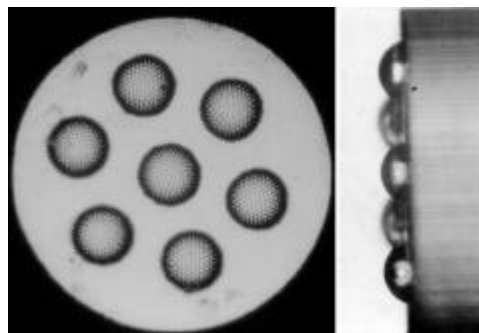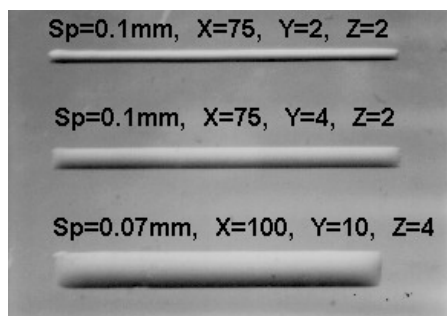

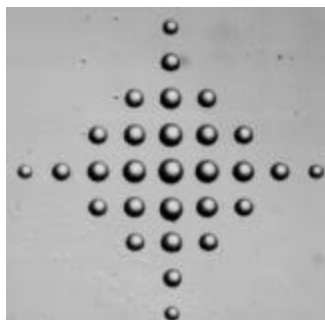*Figure 38: Printed thermoset epoxy lines (top is 300µm wide)*

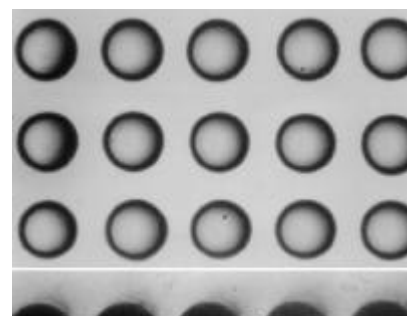*Figure 39: Variable volume printed adhesive spots, >80µm.*

Figure 40: 95µm diam., 34µm high, spacer bumps; substrate plane and profile.

SUMMARY

The capability of ink-jet printing technology to controllably dispense a wide range of materials of interest to MEMS and BioMEMS fabrication has been demonstrated. Materials dispensed include optical polymers, solders, thermoplastics, light-emitting polymers, biologically active fluids, and precursors for chemical synthesis. In addition to the wide range of suitable materials, the inherently data-driven nature of ink-jet printing technology makes it highly suited for both prototyping and flexible manufacturing.

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