Ink-Jet Deposition of Materials for MEMS Fabrication

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Introduction

Micro-Electro-Mechanical Systems (MEMS) fabrication technology has been developed primarily from large volume microelectronics manufacturing technology which relies almost exclusively on photolithographic processes. Photolithographic processes are particularly well suited for large volume, high density fabrication of devices with low process and feature diversity. The prime example is a DRAM memory device with repetition of the same features millions of times. MEMS has successfully built on the huge microelectronics manufacturing equipment and technology base, adding feature diversity by using a limited number of compatible processes. However, MEMS is a field that by definition aims to created integrated micro-devices. If MEMS is to extend beyond the boundaries of it current successes, which are limited to a few applications, it must integrate many diverse functions. Integration of optical functions (Micro-Optical-Electro-Mechanical Systems, MOEMS), biological functions (BioMEMS), and /or sensor functions will require a high level of process diversity, and in many cases at a low density. Thus, these integrated micro-device types are creating a dilemma by driving MEMS fabrication technology away from what photolithography does best (high density) and toward what it does poorly (high diversity).

In addition, many integrated MEMS applications use materials that are simply too expensive to be used with subtractive processes, such as photolithography, where most of the material would be wasted. With the growing investment in nano-technology, it is likely that many more interesting, but expensive materials will be created in the near future. MEMS's current reliance on subtractive processes will limit the utility of these materials in MEMS applications.

A solution to this dilemma is to THINK ADDITIVE. One additive process that has been shown to be particularly well suited to MEMS device fabrication is ink-jet printing technology. In the last decade, ink-jet has come to be viewed as a precision microdispensing tool in addition to its huge success with color printing. Today, this tool is being used in a wide range of applications, including electrical & optical interconnects, sensors, medical diagnostics, drug delivery, MEMS packaging, and nanostructured materials deposition. Ink-jet microdispensing is data-driven, non-contact, and is capable of precise deposition of picoliter volumes at high rates, even onto non-planar surfaces. Being data-driven, ink-jet dispensing is highly flexible and can be readily automated into manufacturing lines.

This paper will illustrate a few of the applications of ink-jet technology that are either MEMS applications or relevant to potential MEMS applications. First, though, we will present a brief background on ink-jet technology.

Background on Ink-Jet Technology

Ink-jet printing technology is actually not a single technology, but a group of different technologies that have a common end result: the extremely repeatable formation of small fluid droplets that can be directed to a specific location with high accuracy. These technologies fit into two general categories. In continuous mode ink-jet printing technology, a cylindrical jet of liquid is formed by forcing a fluid under pressure through an orifice. Surface tension forces create instabilities in the jet, causing it to break up into drops.[1,2] By providing a single controlled frequency disturbance, the jet can be forced to break up at precise time intervals into uniform diameter and velocity droplets. The droplets can be charged by an electrostatic field during their breakup and deflected from a straight trajectory by a second electrostatic field.[3] Charging the drops to different levels allows the drops to be deflected to one of several locations on a substrate, or to be directed into a catcher or gutter for recycling or disposal. Figure 1 shows a schematic of a continuous mode ink-jet printing system. Figure 2 shows a photomicrograph of an array of 70 µm diameter jets of water issuing from a droplet generator device and breaking up into ~140 µm diameter droplets at 40,000 per second.

Continuous mode ink-jet printing systems produce droplets that are approximately twice the orifice diameter. Droplet generation rates for commercially available continuous mode ink-jet systems are usually in the 80-100kHz range, but systems with operating frequencies up to 1MHz are in commercial use. Droplet sizes can be as small as 20 µm in a continuous system, but 150 µm is more typical. Droplets as large as 1mm (~0.5 µl) have been observed.

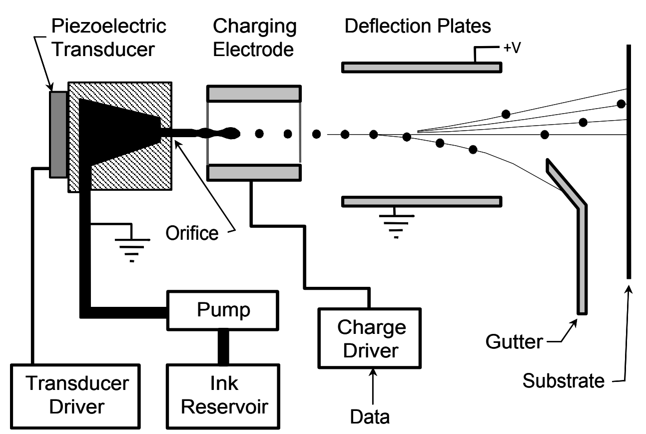

Figure 1. Schematic of a continuous ink-jet printer.

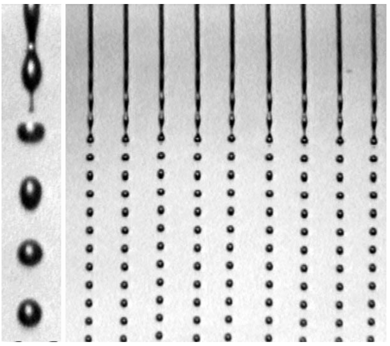

Figure 2. Array of continuous jets with 70 µm diameter breaking up into 140 µm droplets at 40kHz.

Continuous mode ink-jet sys.tems are currently in widespread use for industrial marking, with product labeling of food and medicines being an important application. These systems have high throughput capabilities and are best suited for very high duty cycle applications. Continuous mode systems have been employed in novel applications such as rapid prototyping,[4] electronics manufacturing,[5] uniform sphere or balloon generation,[6] and medical diagnostics manufacturing.[7]

Demand mode ink-jet technology is employed in all SOHO (small office, home office) ink-jet printers. In demand mode systems, a small transducer is used to displace the ink, creating a pressure wave. This pressure wave travels to the orifice[8,9] where its energy is converted to inertial energy, resulting in the ejection of a droplet. A single drop may be generated, or a group of drops at arbitrary intervals of time. Thus the droplets are created "on demand." Demand mode droplets are usually the same diameter as the orifice diameter. Drop diameters of 15-100 µm (2-500 pl) can be achieved with demand mode systems, at droplet generation rates of up to 30kHz. Demand mode ink-jet systems have no fluid recirculation requirement, and as Figure 3 indicates, they are conceptually 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. Figure 4 shows a demand mode ink-jet device generating 60 µm diameter drops of butyl carbitol (an organic solvent) from a device with a 50 µm orifice at 4,000 per second.

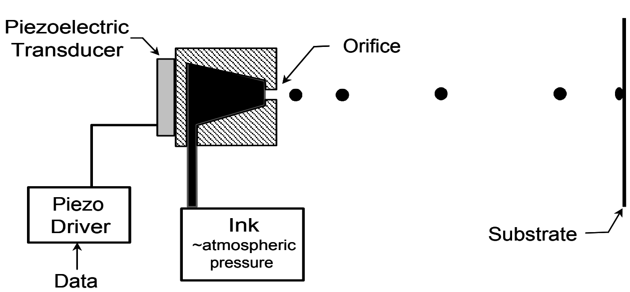

Figure 3. Schematic of a demand mode ink-jet printer.

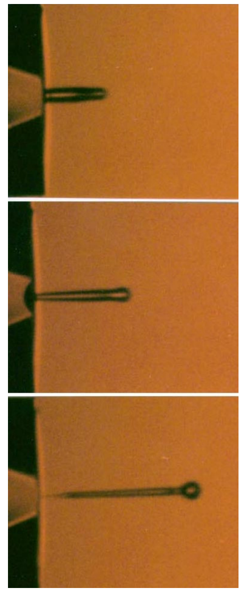

Figure 4. Demand mode ink-jet device generating 60 µm drops 50 µm orifice at 4kHz.

Applications

Electrical Interconnect - Solder Jet®

Solders suitable for electrical interconnects have been dispensed using piezoelectric demand mode ink-jet technology.[10,11] Operating characteristics achieved for jetting of solders include: formation of spheres with diameters of 25-125 µm; 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 (63% Sn/37% Pb), but a number of other solders have been evaluated, including high lead (95% Pb/5% Sn), no lead (96.5% Sn/3.5% Ag; indium; 52% In/48% Sn), and low temperature bismuth solders.

Figure 5 shows results from printing solder onto an 18 by 18 array of pads on a test vehicle, where the pads are 100 µm diameter and on 250 µm centers. The deposited solder volume is equivalent to a drop diameter of 100 µm. The resolution obtainable with ink-jet based deposition of solders is illustrated in , where both bumps and towers of solder have been deposited with 25 µm feature size and at pitches as small as 35 µm.

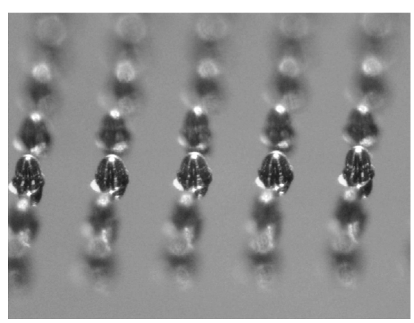

Figure 5. 100 µm solder bumps ink-jet printed onto 100 µm pads on 250 µm centers at 400 per second.

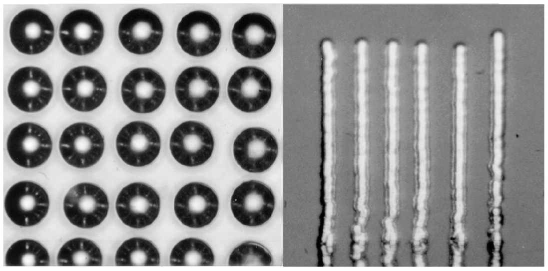

Figure 6. 25 μm bumps of solder on 35 μm centers and 25 μm towers printed on 50 μm centers.

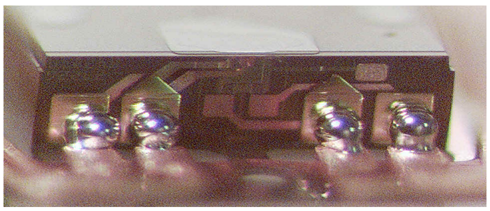

Figure 7. Integrated circuit containing signal conditioning electronics for read-write head of a hard disk drive. IC attached to flex circuit by Solder Jet® technology by placing a solder ball in an inside corner. Pads are 100 μm.

A High level of integration of multiple functions, whether or not one uses the MEMS label to describe them, can lead to electrical interconnect requirements that are very difficult to address by conventional means. One example is the read-write head assembly in hard disk drives. Location of the conditioning electronics as close as possible to the ferrite read-write element allows for increased speed and density. However, a three-dimension electrical interconnect is required in that a solder ball must be placed in the inside corner formed by the conditioning electronics integrated circuit and the flex circuit that connects to the ferrite read-write element. Figure 7.

Electrical interconnect for photonic components in an integrated assembly is another area that requires three-dimension assembly requirements. The most popular solid state lasers used today are vertical cavity surface lasers (VCSELs) where the emitter and electrical interconnect pads are located very close to each other on the top surface of a gallium arsenide wafer. To increase the capacity of data transmission devices, VCSELs are used in arrays. To avoid using wire bonding to electrically interconnect a line array of VSCELs, which is undesirable for reasons of reliability, size, and ease of integration, an inside corner three-dimensional interconnect similar to the disk drive read-write head example above may be employed. Figure 8 shows a VCSEL line array with four emitters electrically connected to a circuit board by an 80 μm solder ball that has been printed into the inside corner using Solder Jet® technology. To perform this operation, MEMS-based tools can be utilized, as shown in Figure 9.

Embedded Passives

Direct-write of electrical passives (conductors, resistors, capacitors, inductors, antennae, and batteries) is being developed for consumer and other electronics applications, including conformal antennae and batteries. Ink-jet is one process being evaluated for these applications.

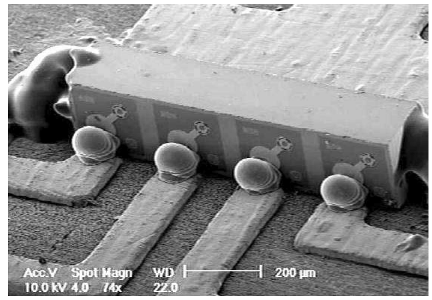

Figure 8. Array of four VCSEL lasers with 80 μm solder ball for electrical interconnect printed into inside corner using solder jet technology.

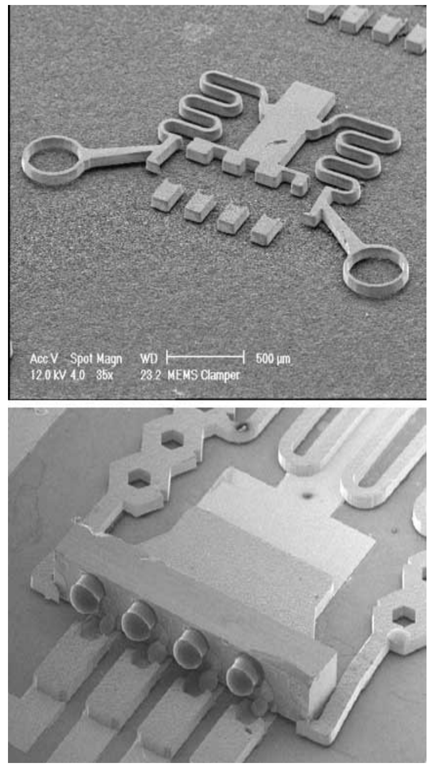

Figure 9. Top, metallic clampers for positioning and metal pads for electrical connections; bottom lensed VCSEL die positioned by clamper & bumped using Solder Jet® technology.

Ink-jet printing of embedded resistors has been successfully demonstrated using both filled polymer and conductive polyimide ink as part of an NIST/ATP project.[12] Figure 10 shows one of the 4-up 18" x 12" embedded resistor test vehicle panels printed using a DuPont proprietary polyimide ink. Resistors ranging from 100Ω/square to several MΩ/square have been created using materials with low resistivity. Printed resistors ranged in size from 125 μm to several mm long.

Conductor printing using ink-jet technology has been demonstrated in the printing of address lines for organic drive electronics used in active matrix displays[13] and antennae. Figure 11 shows an antennae printed at the University of California at Berkeley using ink-jet technology.[14]

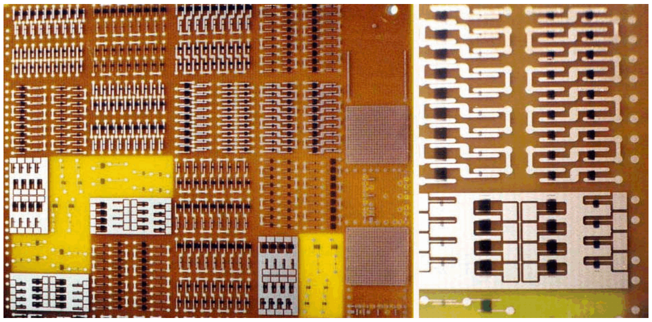

Figure 10. Embedded conductive polymer resistors printed using ink-jet technology, resistivity < 200 Ω/sq. Length of resistors ~1 mm. Left, 100 mm square test panel. Bottom, Enlarged view.

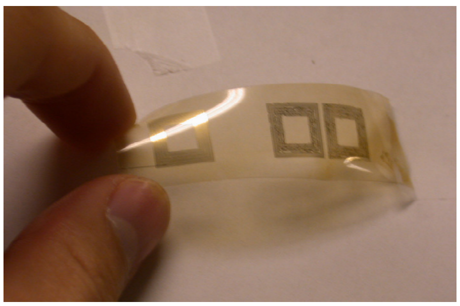

Figure 11. Antennae printed using ink-jet technology. Image courtesy of U.C. Berkeley.

Direct-write capacitors, inductors, and batteries represent significantly greater materials and process challenges than do resistors, but they are possible in principle. A number of research organizations have ongoing research in this area.

Chip-Scale (3D) Packaging

A direct-write chip-scale wafer-level packaging concept, based on both Solder Jet®[15] and Polymer Jet™ technology, is currently under development at MicroFab. First, solder columns with an aspect ratio of two or greater and approximately the same width as the pads are printed onto each pad. High aspect ratio solder columns are used to eliminate the failures associated with thermal expansion mismatch between the integrated circuit and the circuit board. Second, a dielectric polymer underfill is printed onto the die surface and cured (UV or thermal). The polymer is printed around the solder columns to encapsulate them, but it is not printed onto the wafer in the regions that will be sawn with a diamond saw to singulate the integrated circuits. Unlike the highly filled polymers that are currently injected under an integrated circuit that is flip-chip bonded to a circuit board in order to overcome the thermal expansion mismatch problem, the printed polymer serves only to contain the solder columns and protect the device, thus it can be a much lower performance material.

The basic components of the process described above, printing solder columns and dielectric polymers, have been demonstrated. Figure 12 shows a prototype with solder printed into 240 µm tall columns that are placed on 150 µm pitch. After printing the columns, a polymer dielectric was printed into the spaces between the columns.

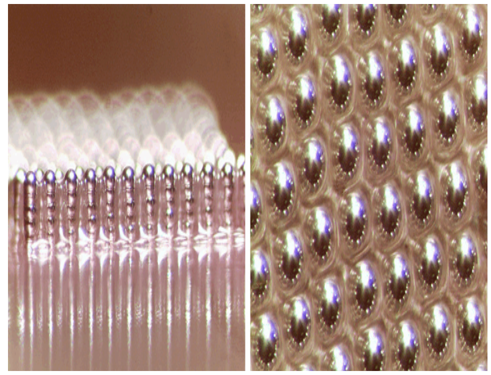

Figure 12. Chip-scale, wafer-level packaging concept fabricated using ink-jet technology: polymer filled solder column array. Columns are 240 µm tall and 150 µm pitch.

Under-Bump Metallization (UBM)

Many organizations are pursuing direct-write of conductors in order to create interconnecting traces on boards, solar cells, RFID tags, etc. One critical application of this technology that has not been widely investigated is creating under-bump metallization (UBM) on the pads of integrated circuits. These pads are normally fabricated using aluminum in the semiconductor foundry. Aluminum is not a solderable surface, necessitating the addition of another metal layer if the device is to be assembled using flip-chip methods.[16] Figure 13 shows the results of printing two different copper inks, using ink-jet technology, and two post-processing methods. Both printing and post-processing were performed in an inert environment (glove box).

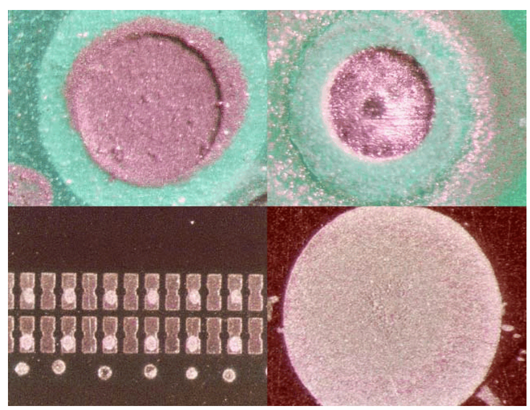

Figure 13. Ink-jet printed copper layers: top left, Cu nanoparticle ink as printed, right laser annealed; bottom left, solution phase copper as printed, right heat converted.

Organic Electronics

Organic electronics is being pursued as a low cost, low performance alternative to silicon based electronics for applications such as radio frequency identification (RFID) tags, display backplanes, and "disposable" consumer electronics. The materials to make organic logic are very similar to the light emitting polymers used in displays and discussed below. Initial efforts have focused on thin-film transistors (TFTs), used principally as drivers in displays. Figure 14 shows a prototype display driver fabricated by Plastic Logic of Cambridge U.K. where the source, drain, and address line for each of 4800 pixels have been printed using ink-jet technology.

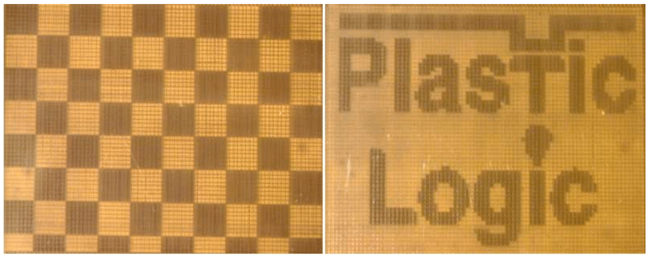

Figure 14. Ink-jet printed active matrix display electronics with 4800 pixels operating at 80 Hz. Courtesy of Plastic Logic.

Displays

Light-emitting polymers are currently being deposited using ink-jet technology by a number of organizations that are developing display manufacturing methods. To construct active elements with these materials, a uniform layer of approximately 100nm must be created in a structure, and the structure must create an electric field across the 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 such as xylene. After deposition, the solvent is driven off and the polymer film is left on the substrate. MicroFab has demonstrated that feature sizes as small as 30μm can be achieved when printing light-emitting polymer solutions onto a surface coated with hole-injection layer material. Figure 15 illustrates the use of ink-jet deposition to fabricate a pixilated display using light-emitting polymers.

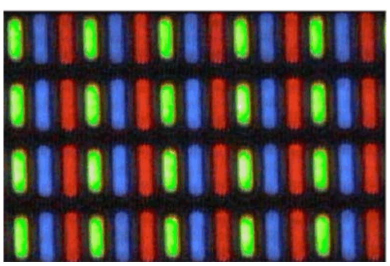

Figure 15. Light-emitting polymer printed into 80 x 100 μm wells in a color display. Image courtesy Dupont Displays.

Microlenses

Refractive microlens configurations that can be printed using ink-jet processes include convex/plano hemispherical, hemi-elliptical and square, and convex-convex. Printed arrays of microlenses, such as those shown in Figure 16, are currently being used in coupling light into and out of optical fibers in micromirror based MEMS optical switches. The array shown in this figure has 400 micro-lenses of 916 μm diameter on 1mm centers. The focal length is 1.10 ± 0.01mm. Diameter and center variation is ± 1 μm.

Smaller diameter lenses at higher packing density and in larger arrays can be used for optical diffusers in LCD displays. Figure 17 shows a portion of an array of 200k lenses, 104 μm diameter and 112 μm pitch, printed using ink-jet technology. The focal lengths for printed micro-lenses may be varied over wide ranges even within a single array. This can be an important performance enhancing feature for optical assemblies that require free-space optical interconnections over relatively long and variable path lengths for different elements of the optical array, as occurs in some micromirror switching devices. Illustrated in Figure 18 are arrays of variable focal length lenses. In the top image is a two dimensional array with variable lens height and diameter. In the bottom image, constant 700 μm diameter lenses are shown in profile with focal lengths of (left-to-right) of 850, 525, 430 and 405 μm.

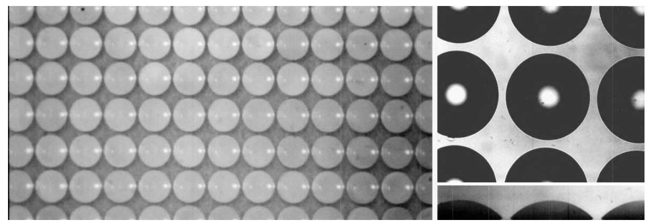

Figure 16. Portion of printed array of 916 μm diameter microlenses, 1 mm centers, focal lengths 1.10 ± 0.01 mm. Diameter, and center variation ± 1 mm for 400 lenses in array.

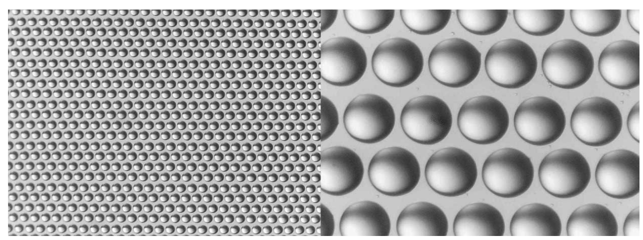

Figure 17. Portion of 200,000 lens printed array, 104 μm diameter and 112 μm pitch.

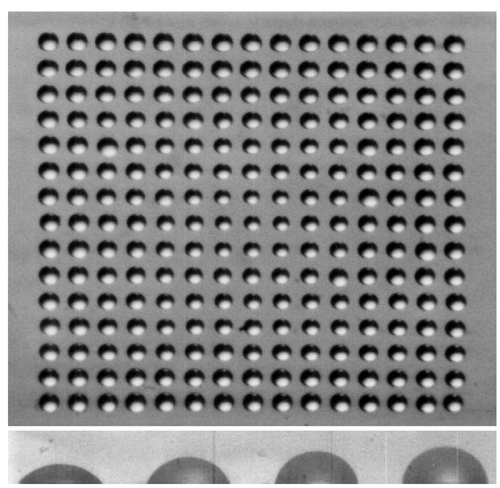

Figure 18. Variable focal length lenses. Top, 2-D array, Bottom, 700 μm diam. Lenses, focal lengths of 850, 525, 430 and 405 μm.

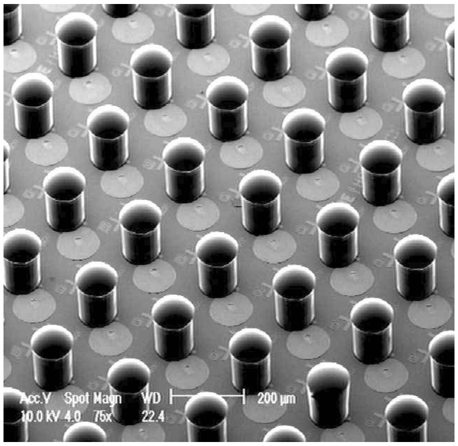

Figure 19. Microlenses printed onto 100 µm tall pedestals to collimate VCSEL output.

Integrated Electro-optic Assemblies

Fabrication of the microlenses over the VCSEL emitters can be accomplished with high quality and at low cost using ink-jet technology.[17] Since it is optically impossible to collimate or focus the laser output using the spherical-section microlenses that can be achieved by ink-jet printing, an offset of the microlens from the emitter plane is required. One way of achieving this in VCSEL array packaging is to print an array of microlenses onto pedestals of optically transparent material on top of each emitter, as shown in Figure 19. Either collimation or focusing of the VCSEL beams at a specified distance from the microlenses can be achieved by adjusting pedestal diameter & height and lenslet radius of curvature.

Waveguides

Printing transmissive optical materials in the form of multi-mode waveguides has been demonstrated using the same optical epoxy material as was used to form microlenses by ink-jet printing. Figure 20 illustrates some of the results that have been obtained. A 1.74-index material is shown printed on glass as 1-16 splitter with 120 µm wide branches, and 125 µm waveguides are shown printed on 150 µm centers. Edge smoothness of the waveguide-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 for use in waveguide applications. However, low loss waveguide materials developed by several materials companies for photolithographic processing can be, and have been in at least one case, formulated to be compatible with ink-jet processes.

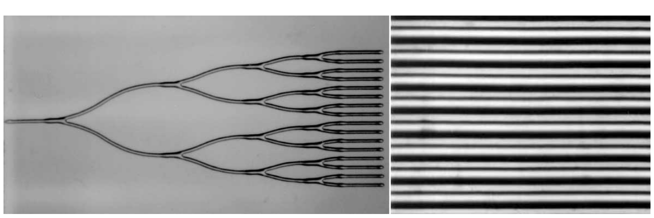

Figure 20. Waveguides printed using ink-jet technology, Left, 1-16 splitter on glass, 120 µm wide branches. Right, 125 µm multi-mode waveguides printed on 150 µm centers.

DNA and Protein Deposition

Early developments in ink-jet printing of bioactive fluids[18] centered on making patterns of antibodies on membrane materials, typically nitrocellulose, that bound the antibody for use in an assay. The pattern was used as a human readable display for the assay. Over one billion diagnostic test strips ($6B value) of this type have been manufactured to date using ink-jet technology.

Miniaturizing antibody assays can increase the number of diagnostic tests conducted in parallel, increase the sensitivity of the assay, and decrease the required sample size by minimizing the amount of both the sample and expensive antibody required for the assay. The MicroSpot™ system[19] of Boehringer Mannheim could contain as many as 100 distinct reactions sites (i.e., spots) in a disposable reaction well shown in Figure 21. Figure 22 illustrates the results obtained from two different immuno-assays in the MicroSpot™ format.

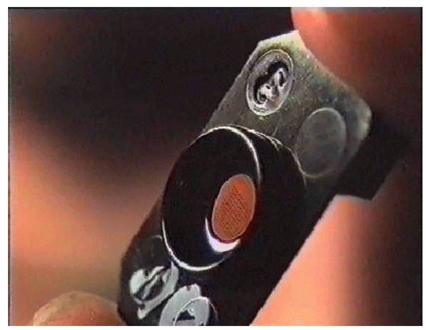

Figure 21. Disposable diagnostic test that contains up to 100 tests printed using ink-jet technology.

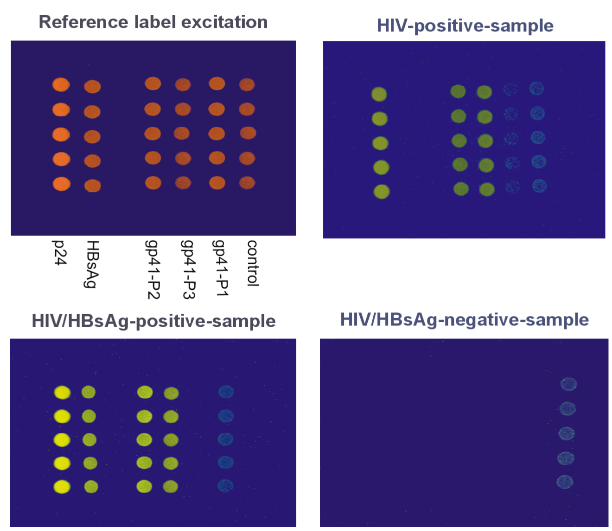

Figure 22. Immunoassay, ink-jet deposited spots ~100 µm (courtesy Boehringer-Roche).

Miniaturized DNA based assays can be fabricated in the same manner as antibody based assays. Figure 23 Illustrates a resequencing assay, fabricated using ink-jet deposition of oligonucleotides, for drug resistant *Mycobacterium tuberculosis* (Mtb).

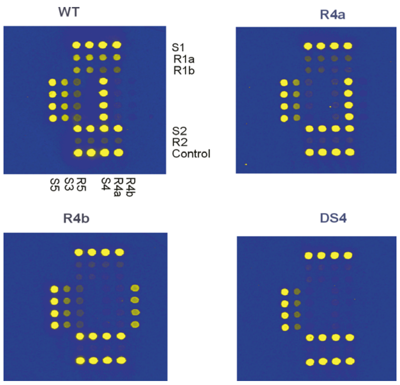

Figure 23. DNA test, drug resistant Mtb., ink-jet despoited spots ~100 μm (courtesy Boehringer-Roche).

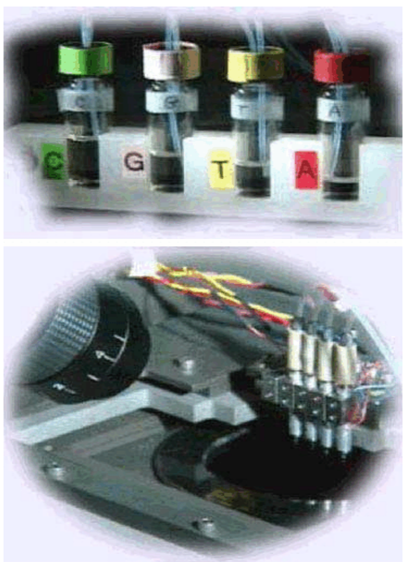

Figure 24. Ink-jet based micro-spot DNA synthesis printer (Protogene Laboratories, Inc.).

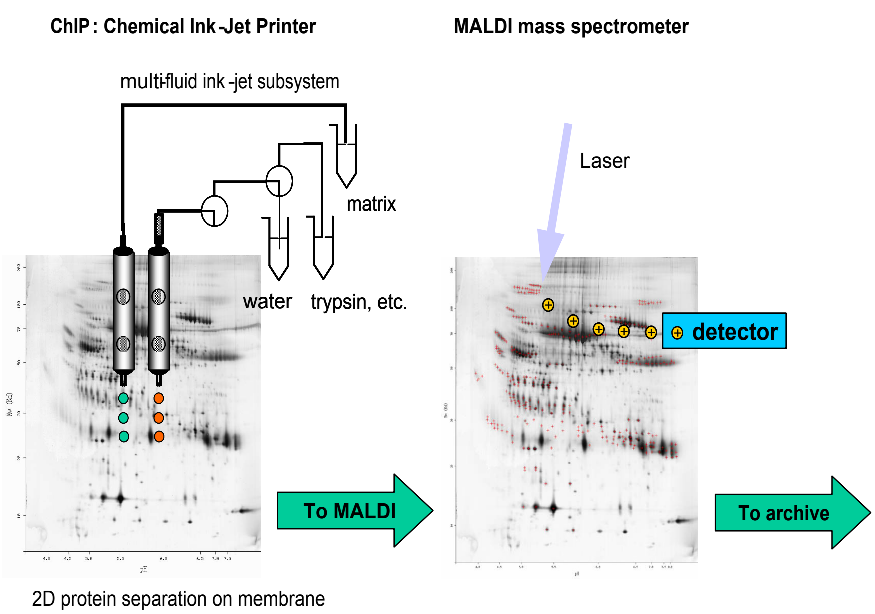

Figure 25. Schematic of chemical ink-jet printer (ChIP) for protein analysis.

In-Situ Synthesis

In addition to being used as a bioactive molecule deposition tool, ink-jet printing methods have been used to perform micro-chemistry, both for synthesis and decomposition. Synthesis of DNA arrays using ink-jet technology greatly decreases the reagent volumes required to create a DNA based micro-assay. For in-situ synthesis, only the precursor solutions of the four constituent bases (A, G, C, T) of DNA, plus an activator (tetrazole), are jetted. Figure 24 illustrates an ink-jet based DNA synthesis system. In addition to DNA synthesis, ink-jet methods have been used to synthesize peptides, which have the 20 naturally occurring amino acids as the building blocks.

Chemical Printing

Ink-jet microdispensing can be used to deliver sample reagents, enzymes, or other sample processing fluids directly to a captured biological sample. This is the principle function of the Chemical Ink-jet Printer (ChIP), which is a product of Shimadzu Biotech, Proteome Systems, Ltd., and MicroFab.[20] The ChIP instrument delivers small volumes of enzymes and reagents to protein samples immobilized on a PVDF or other membranes to prepare the protein samples for MALDI-TOF MS analysis, which is then directly performed on the processed membrane. The protein samples on the membrane have been electrobloted from a 2-D page gel with the proteins separated in one dimension by charge and the other dimension by mass. The enzyme breaks down the protein into peptides, which can be identified by the mass spectrometer. The peptides are then used to identify the original protein by use of a protein database.

Biopolymers, Cells, Growth Factors, Drugs

Biopolymers are currently being printed using ink-jet methods for both tissue engineering and implantable device applications. Biosorbable polymers (PLGA) can be printed into three-dimensional structures to form scaffolds for tissue growth. Cells can be seeded into this scaffold to proliferate and create the desired tissue. Printed growth factors, possibly in complex 3-D distributions, would assist and/or direct the tissue growth. To illustrate, Figure 26 shows 1mm diameter biosorbable conduits for peripheral nerve regeneration fabricated using ink-jet methods. Nerve growth factor (NGF) is embedded in the conduit to stimulate and direct growth.

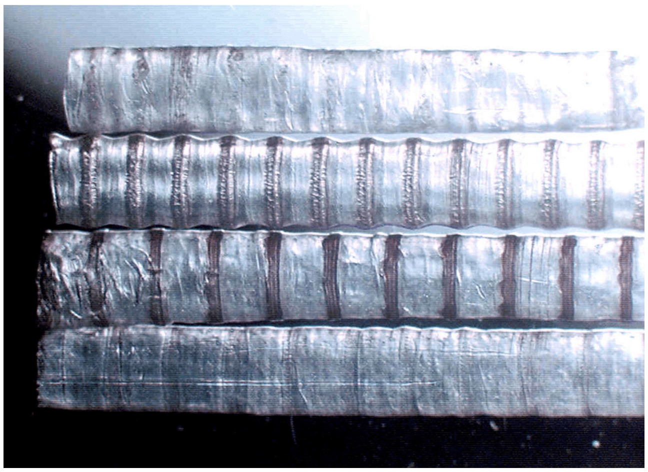

Figure 26. 1mm diameter biosorbable conduits for peripheral nerve regeneration, fabricated using ink-jet printing methods. Nerve growth factor (NGF) is embedded in the conduit to stimulate direct growth.

A recent application of high interest is coating coronary and peripheral stents with drugs and polymers using ink-jet methods. Figure 27 illustrates a typical complex stent geometry, and the precision with which drugs can be jetted onto polymer coated surfaces.

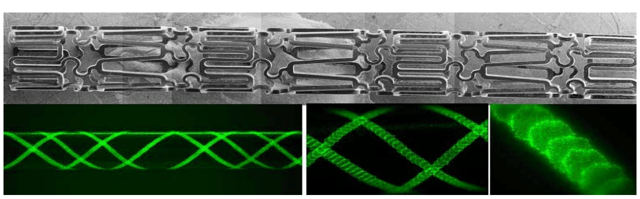

Figure 27. 1.5 mm coronary stent above, 100 μm spots of anti-restenosis drug printed onto 1.5 mm diameter polymer coated stent blank.

Sensors

Chemical sensor materials can be ink-jet printed onto MEMS devices for use in clinical diagnosis, 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 28.

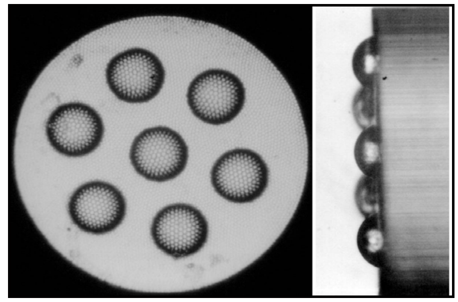

Figure 28. Array of 80 mm diameter indicator elements printed onto 480 mm diameter fiber-optic bundle.

Conclusions

Ink-jet printing methods have been demonstrated for a broad range of processes that are applicable to current and future MEMS applications. The additive nature of ink-jet allows for a high degree of process diversify in fabricating MEMS devices, which should allow a broad range of functionality to be included in a single MEMS device.

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