1 Overview of Inkjet-Based Micromanufacturing

David Wallace

1.1 Introduction

Inkjet technology has come to prominence in the past decade as the dominant printer technology in the combined home and small office/home office (SOHO) markets, and inkjet is now familiar to the general public. Also, in the past decade, inkjet technology has become recognized in the technical community as a highly capable tool for manufacturing, particularly micromanufacturing [1]. As an introduction to the more detailed discussions in the chapters to follow, this chapter will, briefly, give a background on inkjet technology; discuss fluid requirements and pattern formation fundamentals; discuss the characteristics of microfabrication and the potential of inkjet as a tool; discuss the breadth of applications being addressed with inkjet technology, including a few specific examples; and discuss issues, challenges, and possible future applications.

1.2 Inkjet Technology

Inkjet technology is not a single technology, but a family of very different technologies that have a similar function: the precise generation of free-flying fluid droplets. Precise refers to the volume of the droplet, the time at which it is produced, the velocity with which it travels, and the direction of travel. The range of diameter, velocity, and frequency of generation of the droplet obtained, along with the precision, will vary considerably depending on the specific technology employed. A complete discussion of the different inkjet technologies and their relationship to each other is beyond the scope of this chapter and only a brief overview is given below. Excellent overviews of the physics [2, 3] and practical applications [4] of inkjet are available for those interested in more detailed reviews.
1.2.1 Continuous Mode Inkjet (CIJ) Technology

Repetitive drop formation from a cylinder of liquid was noted as early as 1833 by Savart [5] and described mathematically by Lord Rayleigh for inviscid jets [6, 7], and by Weber [8] for viscous jets. In continuous mode inkjet (CIJ) technology, fluid under pressure is forced through an orifice, typically 50–80 µm in diameter, and breaks up into uniform drops under the action of surface tension, by the amplification of diameter perturbations [9, 10] or surface tension perturbations [11]. Piezoelectric actuators have been used as the source of diameter perturbations, but microheaters have been used as the source of surface tension perturbations [12]. A drop breaks off from the jet in the presence of a varying electric field, and thus acquires a charge. The charged drops are directed to their desired location, either the catcher or one of several locations on the substrate, by a static electric field [13].

This type of system is generally referred to as “continuous” because drops are continuously produced and their trajectories are varied by the amount of charge applied. CIJ printing systems produce droplets that are approximately twice the orifice diameter of the droplet generator, which is an important limitation in the use of CIJ in micromanufacturing. Droplet generation rates for CIJ systems are usually in the 80–100 kHz range, but systems with operating frequencies up to 1 MHz have been commercialized [14]. Droplet sizes can be as small as 20 µm in a continuous system, but 150 µm is typical.

CIJ systems are currently in widespread use in product labeling of food and medicines. They have high throughput capabilities, and are best suited for applications where they are in continual use. Very few CIJ systems are multicolor (multifluid), but two-color systems are in use. CIJ systems require unused drops to be recirculated or wasted, another limitation in using CIJ for micromanufacturing. Applications where CIJ is used include Massachusetts Institute of Technology (MIT’s) 3D printing rapid prototyping technology [15], metal jetting technology [16], and medical diagnostic test strip production [17].

Figure 1.1 illustrates a schematic of a continuous inkjet printer and a jet of water breaking up into 120 µm droplets at 20 kHz.

1.2.2 Demand Mode Inkjet Technology

In demand mode inkjet technology, a piezoelectric transducer, or heated resistor that produces a bubble [18], creates pressure/velocity waves in a fluid, which starts at essentially atmospheric pressure, and these waves propagate to produce a drop at an orifice [19–21] or free surface [22]. Since a drop is created only when desired, these types of systems are referred to as drop-on-demand or demand mode. 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 the continuous mode. Driven by the need for multiple orifices to
1.3 Fluid Requirements

The fluid property requirements for demand mode inkjet dispensing are viscosity $<\sim 40$ cP, and surface tension $>\sim 20$ dyn/cm. Low viscosities usually lead to satellite formation (formation of multiple drops when one is desired) and low damping of post-drop oscillations, limiting the upper operating frequency. If the fluid is heated or cooled, the critical properties are those at the operating temperature of the office,

meet the throughput requirement in printing applications, and constrained by the transducer energy requirements, there are many “elegant” (i.e., complex) array demand mode printhead designs [23–26].

Demand mode inkjet systems have been used primarily in desktop printers, and now dominate the low-end printer market (HP’s DeskJets, Cannon’s Bubble Jets, and Epson’s Stylus). Demand mode inkjet systems have no fluid recirculation requirement, and this makes their use as a general fluid microdispensing technology more straightforward than continuous mode technology. Almost all of the results discussed in this book have been obtained with demand mode systems. Figure 1.2 illustrates the schematic of a demand mode system and drops of an organic solvent being formed at 4 kHz.

1.3 Fluid Requirements

Figure 1.1 Schematic of a continuous inkjet printer and a jet of water breaking up into 120 µm droplets at 20 kHz.
not room temperature. Higher viscosities can be tolerated in the fluid delivery system if this does not create a pressure drop that limits the desired maximum frequency due to restriction of the flow into the printhead. For high density fluids, such as molten metals [27] (e.g., solders, tin, mercury, rubidium, and lithium), the fluid properties should be converted to kinematic values to determine if the fluid properties are acceptable.

Newtonian behavior is not strictly required, but non-Newtonian effects are never beneficial. Viscoelastic behavior causes significant performance problems by increasing the amount of deformation the fluid can withstand without breaking off to form a drop [28].

Particle suspensions, such as pigmented inks, are acceptable as long as the particle/agglomerate size and density do not cause the suspension to depart from the fluid properties range given above. Particles that are >5% of the orifice diameter (e.g., cells; [29]) will cause at least some instability in drop generation behavior, but still may be acceptable in low concentrations.

The “window” of fluids and suspensions that can be dispensed using inkjet technology has been enlarged by heating, cooling, stirring, wiping, purging, preoscillating, diluting, and other methods. However, this window is unavoidably narrowed as orifice diameter decreases, frequency increases, and the number of jets in an array increases.

The diversity of fluids that have been dispensed using inkjet technology is impressive, given the fluid property restrictions described above. Inks by themselves represent a broad class of materials. Dye and pigment aqueous dispersions are the most commonly used in conventional printing, volatile, and low-volatility solvent inks are all in common use, as are UV-curing inks. Other materials that have been dispensed using inkjet technology are shown in Table 1.1.
Table 1.1  Materials that have been deposited using inkjet technology.

<table>
<thead>
<tr>
<th>Electronic/optical materials</th>
<th>Biological fluids</th>
<th>Organic solvents</th>
<th>Particle suspensions</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid metals</td>
<td>DNA</td>
<td>Alcohols</td>
<td>Pigments</td>
<td>Sol-gels</td>
</tr>
<tr>
<td>Fluxes</td>
<td>Nucleic acids</td>
<td>Keytones</td>
<td>Cells</td>
<td>Thermoplastics</td>
</tr>
<tr>
<td>Photoresists</td>
<td>Amino acid</td>
<td>Aliphatics</td>
<td>Latex spheres</td>
<td>Thermosets</td>
</tr>
<tr>
<td>Epoxies</td>
<td>Cells</td>
<td>Aromatics</td>
<td>Metals</td>
<td>Acrylics</td>
</tr>
<tr>
<td>Polyimides</td>
<td>Proteins</td>
<td>Dipolar solvents</td>
<td>Teflon</td>
<td>Photographic developer</td>
</tr>
<tr>
<td>Electroactive polymers</td>
<td>Lipids</td>
<td></td>
<td>Phosphors</td>
<td>Fuels</td>
</tr>
<tr>
<td>Organometallics</td>
<td>Biosorbable polymers</td>
<td></td>
<td>Ferrites</td>
<td>Aqueous adhesives</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Zeolyts</td>
<td>Odorants</td>
</tr>
</tbody>
</table>

1.4  Pattern Formation: Fluid/Substrate Interaction

Except for the applications where inkjet technology is used to meter fluid, as in filing a well or a region bounded by a nonwetting coating, inkjet deposition processes are used to produce a pattern of material on a substrate. The interaction between the fluid properties, jetting parameters (drop size, velocity, and frequency), substrate properties, printing grid (dots per inch), and printing sequence (interleave, overprinting, sequence of fluid, etc.) is a multivariate optimization in the development of all inkjet printing systems/applications. For the conventional inkjet case of liquid ink on paper, the porosity of the paper and the low viscosity of the ink represented a major challenge in the initial development of inkjet printers. Rapid spreading of liquid ink through the fibers can cause the spot size to become much larger than the drop size, decreasing the optical density of the spot and resulting in irregular spots that degrade the quality of characters, lines, and so on. Ink formulations that produce good print quality on a wide range of papers have been a cornerstone in the wide acceptance of inkjet printers in the marketplace.

Most micromanufacturing applications of inkjet technology deposit liquid onto nonporous substrates, similar to printing an overhead transparency. Control of the spreading is essential if the desired resolution is to be obtained. Phase change inks were developed for conventional inkjet printers for precisely this reason, since they solidify quickly after impact. In micromanufacturing applications, solders for electronic manufacturing [30] and thermoplastics for free-form fabrication [31] are examples of phase change materials. The control of spreading by solidification is a beneficial aspect of phase change materials if the goal is to limit spreading and obtain the smallest spot for a given drop size. However, if the goal is deposition of a uniform layer, solidification into a bump is a problem, not a feature.
Many organic liquids, such as isopropanol, acetone, and acetonitrile, are of very low viscosity, low contact angle/surface tension, and volatile. Their ability to wet most surfaces and low viscosity allows these fluids to spread rapidly. As with a phase change material’s lack of spreading, this is either a feature or a problem, depending on the application. If one is trying to write a small conductive line using an organometallic ink, or create a pixel in a light-emitting polymer display, it is definitely a problem. In many cases, surface features, such as the wells commonly used in flat panel displays, provide a barrier to spreading and help physically define the feature size. In other cases, surface treatments, such as plasma cleaning or application of a nonwetting coating, are used to control spreading [32].

Volatility of a solution with dissolved or suspended solids can cause operational issues, and ink drying in the orifice is one of the most common failure modes with office inkjet printers. In addition, volatility can cause nonuniform distribution of the solid on the substrate after drying [33]. Solutions to this problem have been many and diverse: reactive substrate, covalent binding of the solid to the substrate, cosolvents that are lower volatility, UV or thermal cross-linking, and so on.

Pattern or image formation in its simplest implementation can be just the selection of pixel (picture element) size and spacing, then using inkjet dispensing to fill the desired pixels, rastering out the image as is done in a conventional inkjet printer. However, even the lowest cost inkjet printers have complicated print modes that are used to increase print quality. Rows of spots are interleaved to hide coherent errors from a single jet, colors are printed so as not to bleed together in wet state, multiple passes are made over an area to increase color saturation of the printed area, and operating frequency is decreased for high-quality printing. All of these methods, and more, have applicability to micromanufacturing applications of inkjet.

1.5 Micromanufacturing

1.5.1 Introduction

Micromanufacturing today has evolved from microelectromechanical systems (MEMS) fabrication technology, developed initially in the 1980s with the goal of integrating electromechanical sensors and actuators with their conditioning electronics. By adding silicon micromachining and deposition of metals and oxides to silicon-based analog integrated circuit (IC) fabrication technology, very small electromechanical sensors and actuators could be fabricated at very low cost and in high volume [34, 35]. In addition, these MEMS-based devices were more robust and reliable than their larger conventional counterparts. MEMS-based accelerometers are the most widely used MEMS products. They have enabled the use of airbags in automobiles and can currently be found in cell phones, computers, cameras, golf clubs, skis, and, of course, video games. MEMS-based pressure transducers
have also been in widespread use for decades, primarily in automobiles, airplanes, process control equipment, and disposable biomedical sensors.

In most applications, the benefits of a high degree of system integration are readily apparent. The success of MEMS-based accelerometers and pressure sensors, along with the general drive toward small, low-cost, high-volume products has led to an explosion of process technologies that can be used in MEMS fabrication and applications targeted by these process technologies. Inclusion of digital electronics was a fairly obvious step. Expansion to optical emitters, detectors, and switches has resulted in micro-optical electro-optical mechanical systems (MOEMS) [36]. Examples include micromirror devices that are used in televisions and projectors, and solid-state laser devices that have enabled the growth of the telecommunication and data communication industries [37]. Inclusion of biological functions has resulted in Bio-MEMS devices [38]. Lab-on-a-chip devices for point-of-care diagnostics are one of the few examples of available Bio-MEMS products [39, 40], although a large number of applications are being developed, including implantable sensors (e.g., glucose) [41] and microneedle-based transdermal drug delivery devices [42]. Finally, by including fluid flow with thermal or piezoelectric actuators, many inkjet printheads fall into the category of MEMS devices and inkjet printers have long been “adopted” by analysts when reporting MEMS industry revenue figures [43].

Many optical devices now included in the MOEMS category do not have a mechanical function, being more properly categorized as electro-optics (EO) devices. Other devices cited above have similar issues when it comes to categorization. This illustrates the difficulty in using the term MEMS in any strict sense at this point in time, since it has been broadened and generalized to refer to micromanufacturing in general, partly as a result of its successes and familiarity. In this chapter, the term “MEMS” is used in the loosest sense, referring to miniaturized devices and systems that must be micromanufactured.

1.5.2 Limitations and Opportunities in Micromanufacturing

MEMS device fabrication methods grew out of the silicon-based semiconductor industry, so most rely on photolithography. Photolithographic processes are particularly well suited for high-volume manufacturing of devices with high feature density and low diversity of fabrication processes and fabricated features [44, 45]. The prime example is a dynamic random access memory (DRAM) device with repetition of the same features millions of times using a limited number of fabrication processes. MEMS fabrication has successfully built on the huge microelectronics equipment and technology base, adding the feature diversity required to create a “system” through a limited number of additional compatible processes. However, photolithography and other “IC-like” fabrication processes are severely limited in the types of materials that can be used. In addition, there are technical and cost limitations that limit the number of “layers” that can be created in fabricating an MEMS device.
Materials limitations in conventional MEMS fabrication fall into two categories, compatibility and cost. First, materials must be compatible with photolithography, which means that they must survive the application, patterning, and removing of photosensitive masking materials, and, in general, must be compatible with the creation of one or more additional layers. Functional materials such as ones that are biologically active, chemically active/receptive, or optically active (emitters and receivers) are typically difficult or impossible to use in photolithographic or other “IC-like” fabrication methods. Yet it is these types of materials that could enable a broad range of new small integrated devices for medicine, security, communications, and so on. Some of the most interesting materials are rare or expensive and thus would be cost prohibitive to use in the current subtractive processes employed in MEMS fabrication. Many biologically active materials fall into this category.

Finally, there is an inherent conflict between the desire to increase the number of functions in MEMS devices and the cost of each “layer” in a photolithographic or other “IC-like” fabrication method. Even if the functional materials are compatible with multiple layers of photolithography and are not particularly expensive, each layer has a substantial total cost (equipment, labor, facility, materials, yield, testing, etc.) associated with it. Thus, additional functions always have a strong cost counterweight in MEMS device design based on current manufacturing methods.

1.5.3 Benefits of Inkjet in Microfabrication

Inkjet printing technology has a number of attributes that can overcome some of the inherent limitations of photolithographically based microfabrication methods. Since it is an additive method, material is only deposited where it is desired. Usage of rare or expensive materials can thus be conserved. The net savings can be significant for even moderately priced materials if the amount of area required to be covered is small compared to the total area of the substrate (i.e., low feature density). In addition to cost savings because of low materials usage, additive methods have little or no waste, so they are much more environmentally friendly. In contrast, subtractive methods waste large amounts of the functional material, plus the photosensitive masking material (if different) and the cleaning and etching solvents.

Since inkjet is noncontact, interaction between different materials when they are deposited is eliminated or greatly reduced, as is the requirement to consider each material to be deposited as an expensive additional “layer.” Deposition can occur on nonplanar surfaces, eliminating planarization steps that are sometimes required in photolithography. Even very fragile or sensitive surfaces such as released layers (thin structures not supported by any solid material underneath them) can be printed onto using inkjet because of the extremely low inertial force exerted by a deposited drop. Active layers (detector, emitter, biological, reactive, etc.) can be deposited onto without degrading their function. Thick films can be created by
overprinting the same location multiple times, and locally layered structures can be created without having to process the entire substrate area.

Lastly, since inkjet is a fundamentally digital, data-driven process, the cost and time associated with producing the masks required by photolithographically based microfabrication methods is eliminated. This removes both the cost and turnaround time associated with fixed tooling. The ability of inkjet to deposit onto individual dye and partial wafers, and to perform parametric process development experiments under digital control, can accelerate the development time for a microfabricated device.

Several examples of the use of inkjet in micromanufacturing are discussed below to illustrate the characteristics and issues of inkjet deposition discussed earlier.

1.6 Examples of Inkjet in Micromanufacturing

1.6.1 Chemical Sensors

Chemical sensors represent a fairly new and broad area of research and development for MEMS devices, driven by the need for large numbers of low-cost sensors for explosive, chemical warfare agents, drugs of abuse, industrial gases, residential gases, and many others. A majority of these sensors use materials that are electrically or photonically active, or more simply have surfaces that cause the molecules of interest to temporarily adhere to them. Not surprisingly, most of these sensing materials are “sensitive,” meaning delicate, and cannot be photolithographically processed. Also, because they are sensitive, they are applied in the last or nearly last fabrication process; typically, this is onto nonplanar, feature-rich surfaces that can be very fragile. All these factors make MEMS chemical sensor manufacturing an area that is broadly exploring the use of inkjet fabrication technology.

Chemoresistive materials, ones that change resistance when exposed to specific molecules of interest, are one of the oldest and most broadly used sensing materials classes used in MEMS sensor devices [46]. Recent developments in nanomaterials and MEMS structures have expanded the number of materials and sensor structures being developed [47]. An example of an MEMS chemoresistive sensor is one that is being developed at Carnegie Mellon University to detect volatile organic compounds (VOCs) in respirators, indicating end of life [48]. The basic sensor structure, shown in Figure 1.3a, is a pair of spiral electrodes in a 250 µm circle that is in a 350 µm diameter SU-8 well. Multiple sensing and reference elements, which, in general, could contain multiple sensing materials, are incorporated on a 2.65 mm die that also contains all the required control electronics, as shown in Figure 1.3b. The die is assembled into a TO-5 package (Figure 1.3c), which is commonly used for optical devices.

The sensing material, gold-thiolate nanoparticles, are suspended in a carrier fluid (5–10 mg ml⁻¹) and deposited onto the sensing area. Although not visible
Figure 1.3 Carnegie Mellon chemoresistive sensor: (a) sensing element configuration showing 250 µm diameter dual electrode spiral in a 350 µm SU-8 well; (b) multiple sensing and reference elements on a 2.65 mm die; (c) sensor device in a TO-5 package; and (d) sensor element printed with 225 nominally 30 pl drops of solution containing gold-thiolate nanoparticles. (Images courtesy Carnegie Mellon University.)

in Figure 1.3a, 15 drops of nominally 30 pl volume have been deposited onto the sensor using an inkjet device. Figure 1.3d shows the sensing area after 225 nominally 30 pl drops of solution have been deposited, producing an average film thickness of 1.5 µm. It is interesting to note the use of two wetting “stops” in the sensing area. The SU-8 well contains the initial fluid volume dispensed, preventing undesired wetting onto other areas of the die. In addition, the fluid dewets from the outer portion of the well during drying so that all of the particles are deposited onto the electrode region. This self-centering behavior results in an impedance variation of <10%.

The dispensing of the sensing material occurs not only on the singulated die but also after it is assembled into the package. This effectively limits the sensing material deposition method to additive dispensing methods, and the requirement to print multiple sensors held in a fixture in a product would require a data-driven method unless the fixture is of high precision (i.e., expensive). If a contact dispensing method is used, throughput would be limited by the requirement for the dispenser to make a vertical movement for each dispense.

Resonant MEMS structures detect a change in resonant frequency associated with a change in the mass of the resonating structure due to the adsorption of molecules of interest. Detection of changes in resonance can be accomplished to great accuracy with well-known electronic circuitry that can be implemented into integrated circuitry on a MEMS device. MEMS fabrication techniques can produce extremely low-mass, high-Q resonant structures that allow detection of very low concentrations of the molecules of interest [49].

1.6.2 Optical MEMS Devices

Refractive optical components in MEMS devices present a number of difficulties. Refractive lens and waveguide features are highly three-dimensional, have high spatial resolution requirements (location, diameter, and curvature), must be highly transmissive, and, in general, should be able to tolerate solder reflow temperatures. Diffractive optical components have been widely employed in MEMS devices because their planar structure allows them to be fabricated using traditional
1.6 Examples of Inkjet in Micromanufacturing

Figure 1.4  SU-8 posts, 100 µm high and 125 µm in diameter, over VCSELs on a gallium arsenide wafer. The posts are on 225 µm center-to-center spacing with polymer lenses printed onto the posts, 22 × 18 pl drops per post. (Wafer with posts courtesy Vixar Corp.)

MEMS processes. However, refractive optics have a higher performance than diffractive optics, making their use in MEMS optical devices highly desirable. By using prepolymer solutions that are cross-linked after deposition, it is possible to formulate jettable polymeric solutions that have no solvents, cure into hard, durable microlenses, and can tolerate reflow temperatures.

Fabrication of lenses onto MEMS devices at the wafer level has advantages in both cost and throughput. Figure 1.4 shows a portion of a gallium arsenide wafer (from Vixar Corporation) containing 125 µm diameter SU-8 posts on 225 µm center-to-center spacing with polymer lenses printed onto the posts (22 drop at 18 pl each). Divergence angle measurements for vertical-cavity surface emitting lasers (VCSELs) with and without lenses printed onto SU-8 indicated a decrease in divergence angle from 11 to 4°. In addition to meeting optical performance requirements, the lens and post-manufacturing processes must not degrade the performance of the VCSEL in terms of threshold voltage and output power. Previous measurements of these for VCSELs with lenses postfabricated using inkjet have shown no degradation in these performance parameters [50]. The capability to print variable lens height, by varying the number of drops, can be used to experimentally determine the optimal lens height very rapidly during development, and can be used in production to create lenses of different height on a single wafer and/or device.

Released structures in MEMS are fabricated onto a sacrificial layer that is subsequently removed, leaving the structure suspended over air (or vacuum). They are frequently employed to allow the structure to move with relatively large deflections. They are very fragile, making application of thick film materials directly to released structures very difficult. Figure 1.5 shows a 100 µm diameter released structure (oscillating micromirror), suspended by 10 µm width/thick supports, onto which a polymer lens has been deposited without breaking or deforming the
1 Overview of Inkjet-Based Micromanufacturing

Figure 1.5 A 100 µm diameter released structure (oscillating micromirror), suspended by 10 µm width/thick supports, onto which a polymer lens has been deposited.

released structure. A nominally 50 pl (46 µm diameter) drop at 2 m s\(^{-1}\) was used to form this lens, making the impact momentum \(\sim 0.1 \mu N \cdot s\).

1.6.3 Bio-MEMS Devices

MEMS devices that are implantable in humans have both great potential and significant challenges. Continuous monitoring and adjustment of biological functions has great potential for more effective monitoring and treatment regimens. However, implantable MEMS devices must deal with biocompatibility and biofouling issues [51]. The implantable microelectrode from the University of Kentucky shown in Figure 1.6 has four 20 × 60 µm electrochemical measurement sites on

Figure 1.6 Implantable (brain) microelectrode with four 20 × 60 µm electrochemical measurement sites on a ceramic substrate. All four sites have been coated with a glutamate oxidase enzyme and overcoated with gluteraldehyde, a fixative, both using inkjet printing. (Images courtesy the University of Kentucky Center for Microelectrode Technology.)
a ceramic substrate that are used to measure brain activity [52]. All four sites in Figure 1.6 have been coated with a glutamate oxidase enzyme and overcoated with gluteraldehyde, a fixative, both using inkjet printing. Since the enzyme coating is thin and transparent, it is not visible in the figure. Currently, this type of probe is used for research into neurological function and diseases such as Parkinson’s. Future variants of this type of device could be used as an indwelling sensor in humans, which would monitor and report brain function as part of an overall treatment plan, similar to blood glucose measurement and insulin injection.

Delivery of drugs by implantable devices [53] is of as much interest as are implantable sensors and current research includes drug delivery for diabetes, cancers, cardiac disease, and neurological disorders. The most widely used implantable drug delivery device today is the drug-eluding stent, used to keep coronary arteries open after an angioplasty procedure. The complex structure of a metal stent must allow the device to collapse to travel through the blood vessels, then deploy (i.e., increase in diameter) and lock at the desired location. To prevent tissue from growing over the stent and blocking the artery again, drugs are embedded into the stent. This requires placing the drug onto one side (only) of complex features 50–150 µm in width. A number of companies are using inkjet for this process [54, 55]. Future coated stents may contain multiple drugs and/or varying concentration with position, for example, placing more drug at the ends, where restenosis (reclosing of the artery) occurs.

1.6.4 Assembly and Packaging

Assembly of MEMS devices presents challenges that are different from and, in general, more difficult than encountered in standard IC packaging. Difficulties include

![Image](image_url)

**Figure 1.7** (a) Top view of signal conditioning IC and flex circuit of disk drive read head assembly. (b) Side view showing 80 µm electrical interconnect pads on IC edge that interfaces with the flex circuit (60 µm traces); solder has been dispensed and partially reflowed into the corner formed by the IC and flex using piezoelectric demand mode inkjet technology to dispense droplets of molten solder.
the inherent three-dimensionality of MEMS devices, fragile structures, hermetic sealing, and so on. An example of a three-dimensional electrical interconnect is the assembly of the signal conditioning IC to the flex circuit containing the read-write head for a hard disk drive. Figure 1.7a shows a top view of the IC and flex circuit and Figure 1.7b the side view. The IC has 80 µm electrical interconnect pads on the edge that interfaces with the flex circuit, which has 60 µm traces. Solder has been dispensed and partially reflowed into the corner formed by the IC and flex piezoelectric demand mode inkjet technology to dispense droplets of molten solder [56].

Most of the recent developments in printed electronics have focused on low-cost, high-volume macroscale devices such as radiofrequency identification (RFID) tags [57]. However, inkjet printing processes for conductors, dielectrics, resistors, capacitors, inductors, antennae, organic transistors, batteries, fuels cells, and other functional elements have been demonstrated and may have application to both MEMS device manufacturing and packaging.

1.7 Conclusions

Inkjet printing technology has been described, including its use in several micromanufacturing applications. Inkjet methods have the potential to drastically increase the range of functions in micromanufactured devices because of the additive, noncontact, data-driven nature of inkjet technology. These same characteristics also can result in lower production cost and in less environmentally unfriendly waste.

Acknowledgments

The author thanks the following for their valuable contributions: Donald Hayes, Ting Chen, Mike Boldman, Virang Shah, David Silva, Bogdan Antohe, Royall Cox, Rick Hoenigman, Lee Weiss, Peter Huettl, and Pooja Talauliker.

References


