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1.12 Low-Cost MEMS Technologies

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1.12.1 Introduction

p0005 While microelectromechanical systems (MEMS) technologies have demonstrated ever more amazing capabilities, the costs associated with MEMS processing have also grown. MEMS and microfabrication technologies have traditionally been dominated by expensive, complicated, cutting-edge equipment. Technologies such as photolithography, dry etching, physical vapor deposition (PVD), chemical vapor deposition (CVD), and related tools that have dominated the MEMS field since its inception are notoriously expensive and rely on processes and components that are inherently costly. Vacuum components, complicated electronics, and precision stages are required for most of these processes and all carry significant price tags. Typical research grade tools usually cost more than US$100 000 and normally a suite of tools is required for any MEMS chip to be fabricated. A basic MEMS research lab often costs more than US$10 million and can be much more expensive depending on the tooling and infrastructure (clean rooms, electrical, and gas systems) required. Manufacturing tools typically run over US$1 million and entire facilities can cost more than US$1 billion. For products where the cost of this equipment and tooling could be spread over millions of units each year, the use of these tools can be easily justified. For potential products where the number of parts each year is less, these large start-up costs can often be prohibitive. In the research arena, the high cost of setting up MEMS facilities often limits research in this field to those institutions with the deepest pockets. In addition, the traditional MEMS technologies are best suited to mass production, but for prototyping, they are often difficult to work with and can again be overly expensive. Thus, over the last decade, extensive efforts have been devoted to developing technologies for MEMS and for microfabrication that are accessible to all researchers, not just those focused on MEMS. Note that the technologies discussed in this work are primarily for generating microscale features between 1 and 100 μm or larger.

p0010 One of the first approaches to reducing costs in MEMS was to move to materials less costly than single-crystal silicon wafers, which is the traditional MEMS substrate. Glass, plastics, and some ceramics have proven to be suitable substrates for many MEMS applications and have also proven to be less expensive. Some of the earliest work in this field combined low-cost materials with some of the traditional MEMS processes that were also low cost, such as wet etching and spin coating to produce glass microchannels (b0470 Manz *et al.* 1990). Some of these materials have also been found to have better properties than silicon for some applications in biology, microfluidics, optics, chemistry, and medicine. As researchers began to explore new materials, new technologies had to be developed in many cases, since the traditional MEMS processes were optimized for silicon or were specific to silicon. Thus, many of the techniques discussed in this chapter are specific to nonsilicon substrates, while others can be used with any material. Many of these new processing techniques have proven to be capable, yet inexpensive. Unfortunately, for chips requiring low linewidths (<10 μm), traditional (or expensive) MEMS techniques have proven difficult to replace, but for MEMS devices where lateral dimensions are not as critical or relatively large (>10 μm) and it is primarily vertical dimensions that are very small (<1 μm), the techniques discussed in this chapter have proven their mettle.

p0015 Low-cost MEMS and microfabrication techniques typically fall into one of the following four categories:

(1) Low-cost photolithography techniques
(2) Photolithography replacements
(3) Rapid prototyping techniques
(4) Low-cost mass production technologies

The first category, low-cost photolithography techniques, is primarily directed toward producing inexpensive photolithography masks. A standard chrome mask on a glass substrate typically costs more than US$5 per square centimeter and can easily be double or triple that amount depending on the

needed quality. For a device that requires multiple masks, the mask-making costs can multiply quickly. In a prototyping situation where several design cycles may be required, the mask cost can be the primary cost driver for a project and can exceed US$1000 per mask. Techniques that may be included in this category are laser and ink-jet printed masks, xurography, and shadow masking using masks made with traditional machining tools. The second category, photolithography replacements, is characterized by techniques designed to eliminate the need for masks, UV exposure systems, optical aligners, and expensive chemicals. The least expensive UV exposure systems of any quality (providing collimated, uniform light) cost at least US$20 000 and systems that provide the ability to align different layers often exceed US$250 000 for basic systems. Techniques in this category include xurography, screen printing, and laser cutting. The third category, rapid prototyping techniques, is designed to eliminate the difficulties and costs associated with producing small-volume prototypes using traditional MEMS tools. Most MEMS processes are fantastically well developed for mass production, since they operate as batch processes, but that also means that it often costs just as much to make one part as it does to make hundreds of parts. Since there is a limited benefit to multiple parts during prototyping, the cost cannot be spread out and can be significant. In addition, microfabrication techniques are typically relatively slow, and even relatively simple designs can take weeks to manufacture and outsourced designs are often not delivered for 6 months or more. Thus, many of the inexpensive prototyping techniques are also much faster, saving money as well as time. Some of the techniques that can be used for low-cost prototyping of MEMS include lamination, xurography, laser cutting, soft lithography, and screen printing. The fourth category, low-cost production technologies, is primarily aimed at technologies for MEMS devices that do not require the substantial infrastructure required for traditional MEMS, but can still produce similar volumes at a relatively lower cost. Techniques in this category typically involve molding, embossing, or stamping. Each of these categories will be addressed in detail in this work. The reader should note that the low-cost techniques can usually be combined with more traditional MEMS techniques to maximize productivity while minimizing cost.

p0020 An important consideration in MEMS fabrication is the packaging of the completed MEMS devices. Conventional wisdom is that MEMS packaging can account for up to 80% of the total cost of a MEMS device, primarily because many MEMS packages must be custom designed. To overcome these packaging costs, a number of approaches have been proposed. The most successful involve modifying or using traditional integrated circuit (IC) packages, but this is often not possible for fluidic or optical systems. Some MEMS designers have managed to essentially eliminate packaging. A few of these methods as well as a few methods for minimizing packaging costs will be reviewed with their related manufacturing techniques.

1.12.2 Low-Cost Photolithography Techniques s0010

Many engineers and scientists have worked to reduce the cost of performing basic photolithography processes or steps. Two primary approaches have been taken. The first approach is to reduce the cost of making the photolithography masks (see Section 1.12.2.1). The second approach is to eliminate the processing steps after photolithography by creating the desired microstructures using the photolithography process (see Section 1.12.2). This approach can be combined with the first approach. A third approach is to eliminate photolithography entirely, which will be discussed in Section 1.12.3. p0025

As noted earlier, standard photolithography masks can be a substantial expense and outsourced masks often take significant time to receive. Most photolithography masks are typically made of precisely patterned UV-absorbing materials such as chrome (most common), iron, or photopatternable emulsions on a glass substrate. Chrome masks are patterned using a tool called a pattern generator, which exposes a layer of photoresist deposited on the metal layer. The photoresist is then developed and the underlying metal layer etched to produce the mask pattern, which can then be reproduced multiple times. The pattern generators are robotic instruments with precise movement and optics to produce high-quality patterns, and are thus relatively expensive. A typical mask can take several hours of machine time to produce, and complex masks can easily take days. The multiple steps required to produce the masks, the precise tooling, and long tool-use times lead to substantial mask fabrication expenses. Thus, to reduce these costs, several alternatives to metal masks have been explored. p0030

s0015 ### 1.12.2.1 Low-Cost Photolithography Mask Fabrication

p0035 Although typical chrome mask generation with e-beam lithography is very accurate (<1 μm feature sizes) it is very expensive (>US$500 per 4 × 4 in mask) and can have a long turnaround time. For this reason, alternatives to chrome mask generation have been evaluated in depth by many groups. Laser printing, microfiche and photoreduction, microscope projection, microfluidics, xurography, and direct laser writing have all been implemented as creative photomask alternatives (Narasimhan *et al.* 2004).

s0020 #### *1.12.2.1.1 Laser printed masks*

p0040 Fabricating photolithography masks by printing the positive/negative mask onto a transparency using laser printing is a common technique. Creating masks with this technique is appealing because it can significantly reduce the cost and time of fabrication (Qin[b0965] *et al.* 1996). High-resolution laser printers can have resolutions from 5000 to 20 000 dpi and can print linewidths down to 10 μm with a local accuracy of 2 μm. The equipment is expensive but there are many outsourcing locations for printing on transparencies (<US$40 per transparency). Laser printers use a process where a photoreceptor, which is a photosensitive drum or belt that rotates, is electrostatically charged. A laser diode is then directed at a moving mirror, which aims the laser beam onto the photoreceptor and reverses the charge wherever it hits. The surface is then exposed to a toner, a fine plastic powder with coloring, and the toner is attracted to the areas on the photoreceptor where the laser beam hit. The photoreceptor is rolled over the paper in order to transfer the image and the paper is then passed through rollers, which provide heat and pressure to bond the toner to the paper. Following toner bonding, the photoreceptor is cleaned and the charge is removed. Therefore, laser printers rely on the spot size of the laser beam generated to determine the minimum feature size, which is determined by the laser quality used. The feedthrough mechanism is also important in providing the local accuracy. The two different methods used are mechanical feedthrough and a fixed internal drum. It has been found that the fixed internal drum is capable of a higher accuracy dot placement (Suleski[b0650] and O'Shea 1995).

s0025 #### *1.12.2.1.2 Photographic pattern reduction*

p0045 Photographic reduction of prints, using 35-mm film or microfiche, can be used to further reduce the feature size capabilities for mask generation (Deng[b0165] *et al.* 1999). This reduction allows the use of a regular office printer to create linewidths down to 15 μm, making mask generation very cost-effective (Deng[b0170] *et al.* 2000). Using a high-resolution laser printer, photoreduction can yield minimum linewidths of 5–10 μm (about US$20 per 10 reductions) (Dotson[b0185] *et al.* 2004). To further reduce feature sizes, microscope projection has been used. A printed photomask is placed in the field stop, diaphragm, of the microscope. Light passes through the photomask and objective and exposes photoresist on a substrate located on the stage. As the light passes through the objective (typically 40× or 100×), the pattern is reduced allowing feature sizes down to 1 μm to be achieved. The main disadvantage of this reduction technique is the limited area that can be exposed, although step and repeat operations could be used (Love[b0450] *et al.* 2001, Whitesides[b0735] *et al.* 2001).

s0030 #### *1.12.2.1.3 Microfluidic gray-scale masks*

p0050 Microfluidics has been used to create photomasks and even gray-scale masks, in order to create 3D structures. The microfluidics are fabricated by first printing a mask with the desired pattern and then exposing photoresist on a silicon wafer. Once the photoresist is developed, poly(dimethylsiloxane) (PDMS) is molded using the photoresist structures and then bonded to a spun PDMS thin layer. Dye is injected into the PDMS channels with varying concentrations. UV light is then passed through the PDMS channels onto a substrate with photoresist. Then, depending on the dye concentration, the developed structures vary in thickness, thus creating 3D structures (Chen[b0115] *et al.* 2003).

s0035 #### *1.12.2.1.4 Masks generated using xurography*

p0055 Photomasks and shadow masks can be fabricated using xurography, a fabrication technique explained in depth in Section 1.12.3.5. For photomasks, a UV-opaque material is chosen to be patterned and the undesired material is peeled away, without removing the backing material. This mask is then transferred and adhered to a glass substrate, thus creating a photomask. For shadow masking, a material is cut with the desired pattern and transferred to a substrate, using adhesive or electrostatic interactions for adhesion. Material can then be deposited over the substrate (i.e., sputtering, PVD, e-beam evaporation). Once the material is deposited, the cut pattern is peeled away, removing the deposited material

where the pattern was adhered. This fabrication technique can provide minimum linewidths of ~25 μm (Bartholomeusz *et al.* 2005).

1.12.2.1.5 Laser electrodeposition for masks

Photomasks have also been developed using direct laser writing on an electroless Ni deposited substrate, an inexpensive deposition method requiring little equipment. This technique can use an inexpensive Ar^+ laser, rather than an expensive pulsed deep UV light source, but takes advantage of a high numerical aperture objective to increase the power density and decrease the spot size of the laser. The smallest feature size generated by this setup was 0.5 μm (Lorenz *et al.* 2004). This technique can provide a relatively simple, economical, and rapid alternative to e-beam lithography while still providing comparable feature size capabilities.

1.12.2.2 Direct Microfabrication Using Photolithography

A number of techniques have been developed to eliminate some of the steps after photolithography, and thereby reduce the total cost of the microfabrication process. These processes include direct fabrication of the microstructure during the exposure process. Examples of this type of work have been completed with both polymers and glass. In both cases, the only step after UV exposure is development using a solvent for the polymers and an acid for the glass.

1.12.2.2.1 Photopatternable polymers

The development of MEMS and microfluidic components often require the use of complex 3D geometries. The rapid fabrication of 3D curves, vias, porous membranes, and tubes have been made possible through the implementation of photoactivated polymers. The basic operating principle of photopatternable polymers is the introduction of a UV source onto a photosensitive polymer, initiating a cross-linking reaction across exposed regions. Excess polymer and reactants are generally washed away leaving the microstructure. Two of the more common techniques used in photopatternable polymers include liquid-phase photopolymerization and SU-8 lithography.

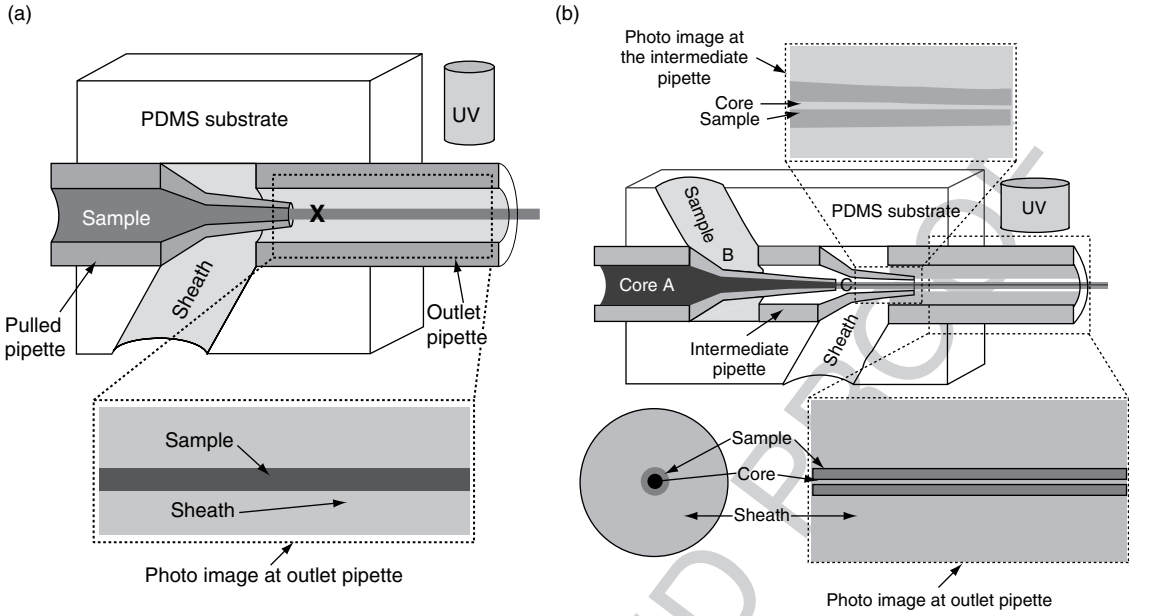
1.12.2.2.1.(i) Liquid-phase photopolymerization

The technique often described as liquid-phase photopolymerization provides a rapid, inexpensive prototyping option for fabricating microstructures. Molds and layered structures are possible in minutes without the use of costly clean room facilities. Variations of this method have been widely explored by Beebe *et al.*, making possible the swift creation of 3D microchannels, filters, fibers, and tubes.

For basic mold or structure patterning, a generic cartridge fixed to an adhesive gasket with the thickness of the desired structure is placed upon a substrate such as a microscope slide and is filled with UV-sensitive polymer through sample inlet ports (Beebe *et al.* 2000, Khoury *et al.* 2002). A photomask is then placed over the cartridge and a UV source exposed to pattern the polymer within the cartridge. The exposed polymer is then flushed with solvent, removing any unexposed polymer waste, thus revealing the patterned structure. The quality of the resulting structures is dependent upon the resolution of the equipment used and the chemical properties of the polymer. Typically, PDMS is poured over the polymer structures and microfluidic channels are created by direct molding. Three-dimensional channel networks can be created by using slight variations on this technique and stacking multiple layers of polymerized material (Mensing *et al.* 2005).

Other complex structures such as fibers and tubes that utilize the microscale characteristics of multiple combined laminar flows and photopolymerization are possible under different configurations (Jeong *et al.* 2004, 2005). The fabrication apparatus consists of a PDMS substrate containing a microchannel, with an inlet and outlet pipette inserted into the ends of the microchannel to provide sample delivery. A separate channel that intersects the inlet pipette is cored into the PDMS to provide sheath flow around the sample flow. A UV source is placed above the outlet pipette to polymerize the sample flow inside the sheath flow in order to produce microfibers. The addition of another smaller pipette inside the inlet pipette enables the addition of a nonpolymerizable core flow that results in microtubes as the sample flow is polymerized at the outlet pipette (**Figure 1**).

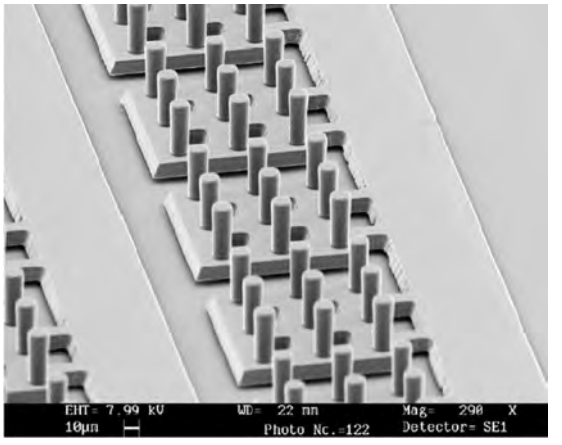
The fabrication of microfilters and porous membranes is accomplished through randomly generated patterning (Moorthy and Beebe 2003). A photosensitive polymer is prepared consisting of monomers, a photoinitiator, a cross-linker, and additives such as water. After the UV source is applied and polymerization has occurred the additive is removed, leaving behind the porous network within the polymer.



f0005 **Figure 1** A representation of the fabrication apparatus: (a) microfibers; (b) microtubes. PDMS, poly(dimethylsiloxane). (Source: Jeong W J, Kim J Y, Kim S J, Lee S H, Mensing G and Beebe D J 2004 Hydrodynamic microfabrication via 'on the fly' photopolymerization of microscale fibers and tubes. *Lab Chip* **4**, 576–80; reproduced with permission from the Royal Society of Chemistry.)

The technique is advantageous for microsystems as the size of the pores is easily controlled by the concentrations of the reagents and the membrane can be created in any location such as a chamber or a microchannel located within a device. The ability to create filter regions locally offers many possible applications in microfluidics.

p0095 s0060 ***1.12.2.2.1.(ii) SU-8 lithography*** The negative photoresist Epon SU-8 or SU-8, which was first developed by IBM, has found wide use in MEMS thick-film-resist applications (b0175 Despont *et al.* 1997, b0390 LaBianca and Gelorme 1995, b0395 LaBianca *et al.* 1995, b0600 Leek *et al.* 1995, Shaw *et al.* 1997). The unique optical properties, harsh environment durability, and lithographic contrast have made SU-8 a popular photoresist for high aspect ratio structures. The use of SU-8 has enabled researchers to produce high-resolution structures for direct molding or protective coatings for electroplating. Drawbacks to using SU-8 include several baking sessions to condition the photoresist and clean room facilities to reduce dust and particles that may affect film quality. However, with proper equipment and facilities, high-resolution, durable processing is possible in an afternoon for a relatively low cost (**Figure 2**).



f0010 **Figure 2** SU-8 pillars fabricated on an array of silicon cantilevers. The pillars are $10 \times 10\ \mu m^2$ in size and 30 µm high. (Source: Conradie E H, Moore D F 2002 SU-8 thick photoresist processing as a functional material for MEMS applications. *J. Micromech. Microeng.* **12**, 368–74; reproduced with permission from the Institute of Physics.)

There are many varieties of SU-8 that have been p0100 developed by varying the solvent contained in the photoresist. The solvent used will generally affect photoresist viscosity and wettability for different types of substrates such as silicon and glass. These

properties will determine the quality and thickness of the spun layer.

p0105 The ability to control layer thickness is an import feature of SU-8 rapid prototyping. Direct PDMS molding and optical waveguides are the most common applications for SU-8 lithography. Tight control of structure width and height has elevated SU-8 to the photoresist of choice for creating microchannels in PDMS (b0020 Anderson *et al.* 2000, b0195 Duffy *et al.* 1998). Also, when producing molded microchannels, there is usually only one mask step, so alignment is eliminated along with the expensive equipment associated with the alignment process. The process of using SU-8 or some other type of mold for PDMS casting is called soft lithography (see Section 1.12.4.1). The SU-8 and substrate surface is chemically coated to allow clean, unhindered peeling of the PDMS microchannel replica. An additional slab of PDMS is placed on top of the grooves to form microchannels. The PDMS layers will combine through an oxygen plasma treatment or partial curing of layers. Following a final bake a single PDMS slab remains with embedded microchannels. Other PDMS microcomponents such as pumps, actuators, and sensors are also possible through SU-8 molding (b0690 Unger *et al.* 2000). While the SU-8 processing is somewhat time-consuming, once a master mold is made, repeated PDMS molding is possible.

p0110 SU-8 can be used to make microchannels directly or by a subsequent bonding step. SU-8 exposure without development followed by a series of SU-8 application and exposure steps can lead to the production of buried SU-8 channels or 3D SU-8 networks (b0275 Gracias *et al.* 2005). Variations of this process using laminated layers of SU-8 can achieve a similar result (b0005 Abgrall *et al.* 2005). Simple patterning of SU-8 followed by a bonding step using adhesives or other materials can be readily used for creating microfluidic channels, though the bonding process is not always simple (b0235 Gale *et al.* 2002).

p0115 Direct use of SU-8 in MEMS components has also been shown to form optical waveguides. Because of the excellent optical properties of SU-8 waveguides, they have been used as biosensors and in other detection schemes (b0105 Chang-Yen and Gale 2003). For rapid and efficient prototyping, direct integration of the optical waveguide reduces coupling losses and interference from the microsystem platform. The direct fabrication of SU-8 into MEMS devices facilitates this integration by removing additional packaging and fabrication steps.

1.12.2.2.2 Photosensitive glass

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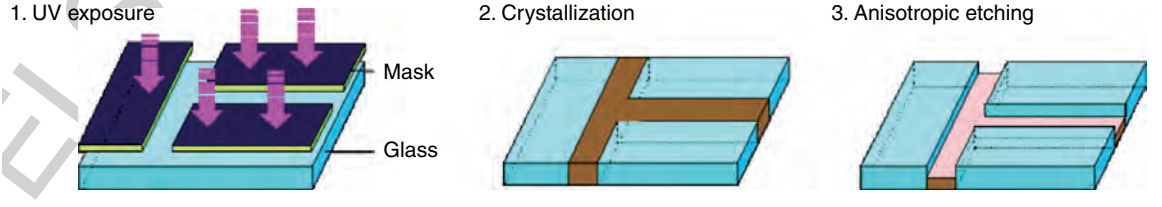
p0120 Photosensitive glass allows for direct fabrication of glass microstructures, which can eliminate a number of later processing steps. In most cases the elimination of the later steps allows for an overall reduction in the cost of device fabrication, which is necessary to offset the relatively high cost of obtaining photosensitive glasses.

p0125 Photosensitive glass has a unique set of characteristics that allow the etch rate of the glass to be modified using common lithographic techniques, creating a 20-fold increase in the etch rate of the modified areas. This physical change allows for direct fabrication of glass structures and makes it possible to create anisotropically etched features in the glass without the need for masking the glass during the chemical etch itself. **Figure 3** shows diagrams for this process.

p0130 The unique chemical behavior of photosensitive glass is due to its special composition. Each brand of this type of glass has a proprietary recipe. The important constituents of all types of photosensitive glass are the introduction of metallic ions – in this case silver (Ag^{+}) – and cesium oxide (CeO_2) into the glass matrix (b0640 Stookey *et al.* 1978). When the photosensitive glass is exposed to UV light or other high-energy sources such as a proton beam (b0265 Gomez-Morilla *et al.* 2005), infrared femtosecond laser (b0305 Hongo *et al.* 2005), or X-rays (b0610 Shimizugawa *et al.* 2003), the cesium



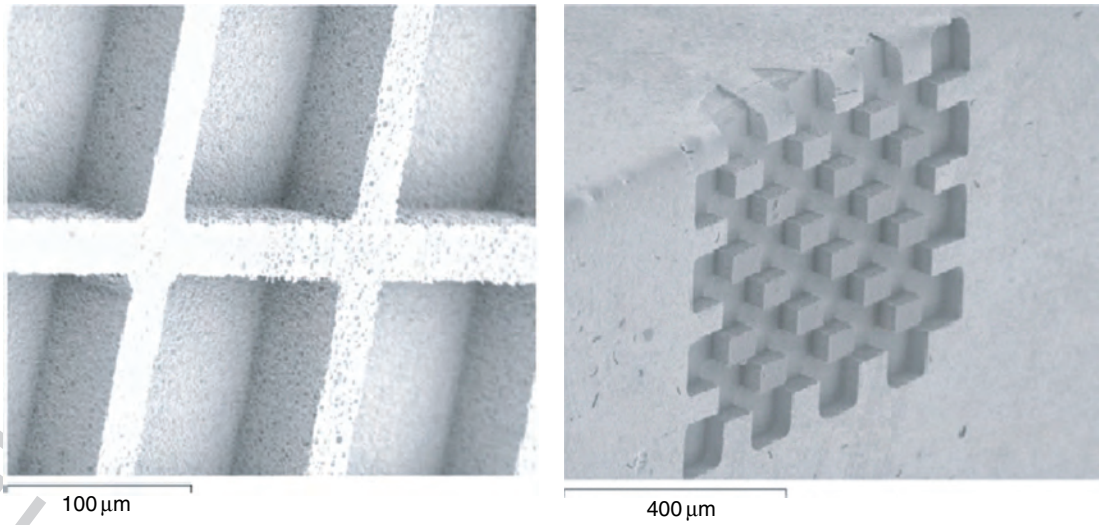
f0015 **Figure 3** Microfluidic structures can be fabricated in photosensitive glass by first masking and exposing the glass to UV light, then heat treating the glass, and finally covering the entire surface with an HF-containing solution.

causes the metals to precipitate out of the glass matrix. The nucleation of the metals and other additives during heat treatment causes a visual discoloration of the exposed areas and a local weakening of the molecular network. It is this alteration of the glass matrix that causes the exposed areas to etch at rates much higher than the rates for the unexposed regions. Because of these unique properties, photosensitive glass has some distinct advantages and disadvantages. Since the chemical etch is anisotropic in nature, virtually straight sidewalls are formed. This contrasts with the curved etch profile associated with isotropic etching. In addition, photosensitive glass can be etched with high aspect ratios, while the typical isotropic etch can never be more than half as deep as it is wide. **Figure 4** shows a structure that was formed by anisotropically etching photosensitive glass.

p0135 Photosensitive glass is often used to create microfluidic channels, which requires another layer to seal or close off the channel. Multiple layers of photosensitive glass may be bonded using fusion bonding techniques (Olsen and Serpa 1978) and other traditional glass-bonding methods such as pressure-assisted bonding, chemical bonding, water bonding (b0030 Ito *et al.* 2001), and glass–metal bonding. Anodic bonding is not typically used with photosensitive glass due to mismatch problems in the thermal expansion coefficient between the glass and silicon. Other channel sealing methods using tapes, PDMS, and other polymers have been demonstrated. Embedded 3D channels have also been created in photosensitive glass using femtosecond lasers (b0475 Masuda *et al.* 2003), but this technology is certainly not inexpensive.

1.12.3 Photolithography Replacements s0070

p0140 A number of techniques have been developed to circumvent the need for any photolithography steps in the production of microscale devices. These techniques typically use some sort of cutting or machining process to produce microstructures that can then be reproduced using molding. For those techniques not amenable to later molding, the processes, even though they are serial in nature, are sufficiently fast and inexpensive that they can easily compete with photolithographic processes. Some of these processes, such as ink-jet printing and screen printing can be direct replacements for photolithography since they can be used to deposit a resist material directly. Microcontact printing (μCP) can also be used to deposit resists and other materials as a replacement for photolithography, but as it is a subset of soft lithography, which is discussed elsewhere (Section 1.12.4.1.2), it will not be discussed here. Techniques such as xurography and laser cutting of laminates produce microdevices directly (or masks



f0020 **Figure 4** Features made using an anisotropic etch in photosensitive glass. (Source: Gomez-Morilla I, Abraham M H, de Kerckhove DG, Grime G W 2005 Micropatterning of foturan photosensitive glass following exposure to MeV proton beams. *J. Micromech. Microeng.* **15**, 706–9; reproduced with permission from the Institute of Physics.)

directly) and can eliminate not only the photolithography process, but all of the subsequent etching and deposition processes.

p0145 Traditional machining techniques are also beginning to enter the microdomain and impressive demonstrations of efficient, relatively inexpensive devices fabricated using micromilling, microelectro discharge machining (microEDM), and related technologies are becoming more common (Hupert *et al.* 2006). These techniques, though, tend to be serial and very slow, so they are typically only useful for making molds that are later used to produce microdevices. Thus, they will not be explored further here, especially since there is significant literature already available on these traditional techniques.

s0075 1.12.3.1 Ink-Jet Printing

p0150 In general, two types of deposition methods are used with ink-jet printing: continuous-mode technology and the more frequently used drop-on-demand (DOD) technology. The continuous-mode print head uses a pressurized fluid chamber to create a continuous fluid stream, which is divided into droplets by pulsing the fluid with a transducer. These droplets are electrostatically charged and are able to be deflected in order to either hit or miss a moving target substrate. The DOD method uses a volumetric change, at ambient pressure, in the fluid to create droplets either by the displacement of a piezoelectric element (Wallace 1989) or by forming a bubble in the ink by heating a resistive element (Aden *et al.* 1994).

s0080 *1.12.3.1.1 Feature size capabilities*

p0155 For ink-jet printing, the properties of the print head, the substrate material, the dispensed ink, and the mechanical resolution of the printer are key factors in determining the minimum feature size capabilities. The dispensing head of ink-jet printing determines the amount of fluid dispensed per deposition. The DOD method is preferred because it is able to form much smaller droplets (~20–100 μm in diameter) than the continuous-mode system (diameters up to 0.5 mm may be produced). Also, the continuous mode has relatively high priming volumes and is not very consistent for droplet placement. The piezoelectric print head is usually chosen over DOD with microfabrication because it allows a larger range of ink compatibility when compared to the thermal print heads, which are generally limited to water-based inks, unless the head is redesigned for each differing solvent that is desired to be used within the ink.

p0160 The temperature and hydrophobicity/hydrophilicity of the substrate material are important in providing minimum microfeatures. Heating the substrate that the ink will be deposited on, generally in the range of 100–300 °C, improves the deposition quality. One reason for this is that the evaporation of the ink is almost immediate once in contact with the substrate, thus eliminating many wetting problems such as surface tension causing bulging or pinching, uneven surface wetting due to contamination, dust particles that can wick the ink, and scratches that may be on the surface, which creates a capillary effect causing the ink to spread. Also, with rapid ink evaporation, multiple layers can be deposited relatively easily and quickly (Fuller *et al.* 2002) to form 3D structures (Gothait 2003). The surface chemistry (hydrophobic or hydrophilic properties) is also important in defining the minimum feature size. Hydrophilic and hydrophobic regions can be defined on the substrate surface to help control where the ink is deposited by having the ink attracted to certain regions and repelled from others (Sirringhaus *et al.* 2000). These surface regions can be fabricated on the substrate surface using common microfabrication techniques or inexpensive alternative methods.

p0165 The dispensed ink composition is another important attribute. Viscosity, evaporation rates, surface tension, solvent used, and adhesion promoters are important properties for ink. High viscosity and low evaporation rates are generally recommended for dispensing because the print head is less likely to get clogged. The surface tension and ink-base chemical makeup plays a key role in determining how much the ink will spread once in contact with the substrate. Several solvents that change the homogeneous film formation on the substrate (water, terpineol, acetophenone, anisole, butyl acetate, ethyl acetate, methyl benzoate, toluene, and *p*-xylene) can be used (Tekin *et al.* 2004). The adhesion promoters within the ink determine how well the ink will bind to the substrate. For conductive inks, the size, dispersion, and stability of the metallic nanoparticles in the ink are very important. Clogging can occur if the particles are too large or if aggregation occurs among the metallic nanoparticles. These physical properties also determine the conductivity performance of the metallic ink once deposited on the substrate.

p0170 The mechanical resolution of the ink-jet printer plays a role in the quality of microfeatures

achievable. This depends on the mechanical resolution of the print axes. Accurate positioning of the ink-jet head allows for less dimensional errors when fabricating devices and determines minimum linewidth and minimum spacing between features.

s0085 ***1.12.3.1.2 Ink-jet printing applications***

p0175 Applications for microfabricating devices using ink-jet printing technology includes solder printing, conductor trace printing, printing of adhesives and dielectrics, printing of optical polymers, and multiple-layered structures.

p0180 Ink-jet printers have been found capable of depositing conductive (Lee *et al.* 2005, Mei *et al.* 2005) and magnetic inks (Voit *et al.* 2003) efficiently and, therefore, ink-jet printer speed and resolution have been used for addressing specific electronic fabrication needs and creating magnetic mass storage patterns. The deposition of solder bumps on circuit boards and even fabrication of the entire circuit board – the traces, dielectric coating, and solder bumps – all using an ink-jet printer has been demonstrated. It has been shown that up to 600 bumps per second can be achieved using this technology without needing to have contact with the board during fabrication, thus providing the electrical interconnects necessary. Solder bumps as small as 24 µm have been printed (Hayes *et al.* 1999a). Furthermore, it has been shown that the entire circuit board interconnects can be fabricated using solely ink-jet printing. **Figure 5** shows a diagram of how the traces, dielectric coating, and solder bumps could all be fabricated with an ink-jet printer (Hayes *et al.* 1999b).

p0185 Printing of thermosets, thermoplastics, and UV-curable adhesives can also be deposited (Meyer 2001) for component bonding or even for the creation of waveguides. For this application, wettability between the surface and the deposited material is important. If the surface energy of the substrate is too high, the adhesion to the subsequent material may not work well. A low-wetting coating can help the flow of adhesive on the substrate without adversely affecting the adhesion.

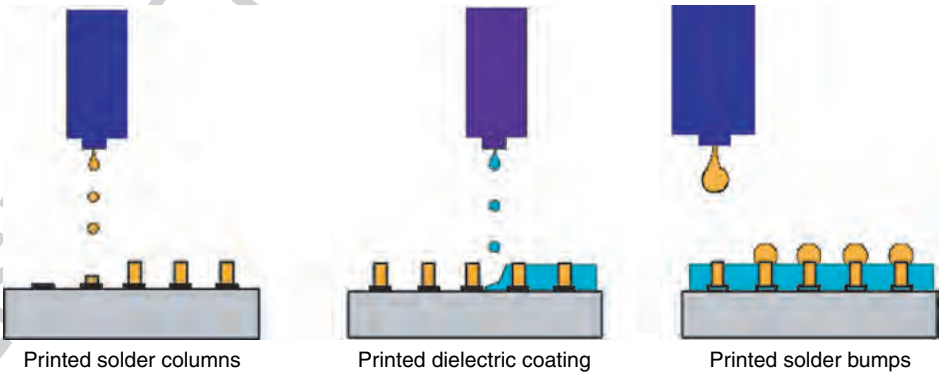
p0190 Three-dimensional ink-jet printing is now regularly used to do rapid prototyping of all kinds of devices (some rather large). On the microscale, some of the most interesting applications include fabrication of microfluidic devices (Cooley *et al.* 2001) and tissue engineering (Saunders *et al.* 2005).

1.12.3.2 Screen Printing

s0090

p0195 Screen printing is able to provide an inexpensive and versatile manufacturing method for depositing material on almost any surface with precision. This fabrication technique is able to minimize the amount of material waste during deposition by directing it to specified locations, unlike the traditional techniques of spin coating and PVD, which are incapable of this material control. It has been found that screen printing can achieve linewidths and line spacings down to 50 µm (Hughes and Ernster 2003).

p0200 The basic principle of ink deposition using screen printing is to pass a squeegee over a screen, forcing ink through the screen onto a substrate. Off-contact printing and contact printing are the two main

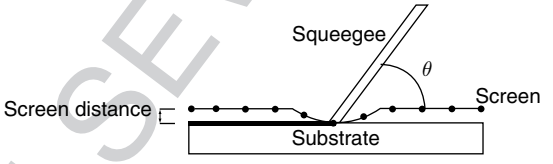


f0025 **Figure 5** Process diagram for building chip-scale packages by printing solder columns, followed by a dielectric coating between the solder columns, and finally the solder bumps on top of the solder columns. (Source: Hayes D J, Wallace D B, Cox W R 1999 Microjet printing of solder and polymers for multi-chip modules and chip-scale packages. *Proc. IMAPS Int. Conf. High Density Packaging and MCMs*, Denver, CO, USA, pp. 242–7. © 1999, reproduced with permission from IMAPS – International Microelectronics and Packaging Society.)

methods used. Off-contact printing allows the screen to be in contact with the substrate only where the squeegee is located and is the most commonly used technique. Stretching the screen mesh, by applying pressure to the squeegee, causes the screen to come in contact with the substrate and forces the ink particles to pass through the screen. When the screen is released from tension it snaps back, leaving the ink adhered to the substrate, as illustrated in **Figure 6**. Contact printing allows the entire screen to be in contact with the substrate during the printing process and the ink is deposited on the substrate by the force of the squeegee applied to the ink particles. Following ink deposition using one of these methods, the ink is allowed to settle and is then dried, generally between 100 °C and 150 °C, in order to evaporate the solvent out of the ink. Heat treatment may then be given to the dried ink by firing it in a kiln at a temperature between 600 °C and 900 °C (Jeong *et al.* 2001).

p0205 Screen printing components include the ink, squeegee, stencil, screen, and substrate. Each of these components introduces variables into the system that will need to be optimized:

(1) The properties of the ink: The ink viscosity affects the printed thickness of the substrate – the lower the viscosity the thinner the print. Drying and firing cause the ink to shrink and must be accounted for when designing a stencil.
(2) Screen printer settings: If the screen distance is small and the screen tension is less, ink will remain in the screen; if it is too large, a thicker pattern that can damage the screen is generated. The faster the squeegee passes over the screen the thinner the film, but if this is too fast it could result in gaps or inconsistencies within the printed pattern. Increasing the squeegee pressure can result in a thicker print. The increased angle and differing geometry of the squeegee can also increase pressure on the ink, yet it does not increase pressure on the screen.
(3) Geometry of the stencil: The tolerances and feature sizes of the stencil generated on the screen determine the minimum feature sizes available for the printed pattern.
(4) The screen: The mesh size, mesh material, and wire diameter/geometry help determine the thickness of the film printed – the smaller the mesh the thinner the print.
(5) The substrate: If the substrate is not flat or not parallel to the screen, film thickness will vary across the substrate (Jabbour *et al.* 2001, Parikh *et al.* 1991).



f0030 **Figure 6** Illustration of off-contact screen printing method. The screen distance and squeegee angle are defined. As the squeegee passes, the screen is stretched to contact the substrate, while forcing ink particles through the screen simultaneously. Once the screen is released from tension it snaps back to its original position, leaving the ink adhered to the substrate.

Many applications of screen printing for microfabrication have been demonstrated. One common use is in generating solar cells that are up to 15% efficient in using screen printing fabrication (Doshi *et al.* 1996, Rohatgi *et al.* 2003, Sakai *et al.* 2005). Screen printing has been used to produce disposable electrochemical sensors (Xu *et al.* 2004). A thick-film screen printing has been used to create diaphragms within ceramic capacitive pressure microsensors (Sippola and Ahn 2005). Flip chip packaging has used screen printing of solder as an inexpensive fabrication method (Chow *et al.* 2000). Fabrication of photodiodes with a response time of 0.32 s and a rise time of 0.48 s has also been achieved using screen printing (Yahaya *et al.* 1998). p0210

1.12.3.3 Stamping s0095

Stamping relies upon the fabrication of a master mold that can generate replica patterns. Molds for creating stamps are typically etched structures in silicon wafers, lithographically patterned SU-8, or electroplated metals. Polymeric materials that are soft and elastic are typically used for the molding of the stamp contact head. PDMS works well for most stamping applications due to its transparency, flexibility, and biocompatibility. For high-resolution applications, more rigid materials are required for the stamp head. However, a trade-off occurs as more rigid materials do not provide the same levels of surface contact that flexible materials provide. In these cases a combination or hybrid material can be used to attain a high degree of contact and resolution. Other important parameters to consider when using p0215

stamping processes are the aspect ratios of the patterning features. For high aspect ratio structures, a tendency to buckle is possible depending on the flexural strength of the material and the applied pressure necessary. Low aspect ratio structures, if spread far apart, may experience bowing from the bulk material between structures that may impede clean stamp patterning. Stamping in microfabrication is typically referred to as microcontact printing and is discussed in much greater detail in Section 1.12.4.1.2.

s0100 p0220

1.12.3.4 Laminate Microfabrication

Laminate, or layered, fabrication approaches have been developed to enable device assembly from thin sheets of polymer plastics, SU-8 films, photopolymer dry films, PDMS, and other materials. Because of their relatively inexpensive and easily machinable characteristics, polymers have moved to the forefront as materials used for rapid prototyping and fabrication. Polymer laminates have much to offer in the field of MEMS because of their ability to make 3D microfluidic devices that can be passively or actively driven by interfacing with other components. Laminate fabrication techniques allow for quick fabrication times, reduced costs, and 3D structures that are capable of incorporating hybrid elements such as electrodes, filter membranes, pumps, and sensors. Although the use of hybrid elements complicates fabrication and design since multiple patterns and a difficult assembly process are required, rapid fabrication methods, cheap material selection, and simple bonding techniques make laminate fabrication possible and useful (Sasserath and Fries 2002[b0590]). Laminate MEMS fabrication has been demonstrated commercially as the primary fabrication method used by a company called Micronics based in Washington, USA. The company uses laminate technologies to do both rapid prototyping and commercial production of microfluidic chips for researchers and businesses. Presented here are methods and techniques demonstrating how laminate microfluidic chips can be quickly patterned and bonded together to make 3D microfluidic devices. The limitations of the different techniques are discussed and the major applications presented.

s0105 p0225

1.12.3.4.1 Laminate materials

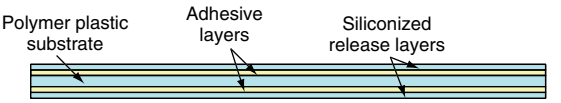
Laminate microfluidic chips can be made using a variety of materials and fabrication methods. The two most common materials are thin polymer plastics, which can be bonded using adhesives or thermal processes, and PDMS, which can be bonded using surface plasma treatments and pressure, or thin layer cross-linking and baking. Other laminate layering methods include SU-8 and dry film photoresists that can be photopatterned using photolithography and bonded together to form multilayer laminate structures.

s0110 p0230

1.12.3.4.1.(i) Polymers Thin polymer sheets, such as Mylar or polystyrene, are commercially mass produced and can be purchased to fabricate polymer laminate chips. These materials are typically ordered as large rolls of thin sheets or can be purchased as smaller precut sheets. Sheet thicknesses can range anywhere from 10 μm to hundreds of microns if desired. Sheets can be made of different polymers and can be coated with various adhesives depending on the desired application of the laminate card and the intended use of buffers and samples. The thin polymer sheets and adhesives are assembled as a five-layer sandwich consisting of the polymer, adhesive layers, and siliconized release layers, as shown in **Figure 7**. The polymer and adhesive materials are generally compatible with aqueous solvents and their selections may vary depending on the solutions with which it will interface. The sandwich of polymer, adhesive, and release layers can all be patterned at the same time and are most practically and inexpensively patterned using a CO_2 laser.

s0115 p0235

1.12.3.4.1.(ii) SU-8 films SU-8 is a commercially available negative-resist photopolymer that can be spun on to a release substrate and patterned using UV light. The unexposed SU-8 is then typically etched away using an SU-8 developer leaving the patterned SU-8 structure behind. If the SU-8 is spun on to a thin release layer such as polyester (PET), the thin layer of SU-8 can be dried and then attached to another layer of SU-8 using plasma treatment and a slight pressure. The non-cross-linked SU-8 layer can then be cross-linked by UV light passing through the thin PET layer and the uncrosslinked SU-8 will be peeled away along with the PET layer, resulting in a dry release of the SU-8 (Abgrall *et al.* 2006[b0010]).



f0035

Figure 7 Illustration of how sandwiches of Mylar, adhesive, and release layers are patterned and assembled together.

p0240 s0120 ***1.12.3.4.1.(iii) Dry film photoresist*** Dry film photoresist tape is a prefabricated thin sheet of negative photoresist that is intended to be photopatterned using UV light, quickly bonded to another substrate, and developed using a photoresist developing reagent. Its advantages include reduced process times, reduced UV light intensity exposure, and uniform photoresist thickness. One example of its use is to form photopatterned channels and to sandwich it between two layers of different materials to form microfluidic channels. The use of SU-8 and dry film photoresist layers allows for smooth surfaces and smaller channel thicknesses because of its use in photopatterning, but still requires expensive photomasks, photoresist development, and UV sources and alignment (b0685 Tsai *et al.* 2006).

p0245 s0125 ***1.12.3.4.1.(iv) Poly(dimethylsiloxane)*** PDMS is another material that can be used to form 3D laminate microfluidic components and is relatively inexpensive when compared to glass. Some of the advantages of using PDMS include cost, bond strength, softness/deformability, thermal properties, and transparency. PDMS is a soft two-part polymer that is patterned by pouring a thin layer of uncrosslinked PDMS on photopatterned structures, such as SU-8, or by a process of injection molding, then cured using heat or other cross-linking activation processes. Multiple-patterned structures of PDMS can be assembled together using a plasma treatment and pressure, or by applying a thin coating of uncrosslinked PDMS between two partially cured layers, which will create a hermetic cross-linking between each layer when completely cured. This technique has been used to develop a protein array printing method using continuous flow microspotters fabricated from five separately patterned layers of PDMS using injection molding (b0110 Chang-Yen and Gale 2005). Some disadvantages associated with PDMS are channel collapsing and poor adhesion effects if channels are too small or too close together. In addition, this material must usually be patterned on the surface of another mold or pattern, which reduces its rapid prototyping abilities and increases costs.

s0130 ***1.12.3.4.2 Laminate patterning methods***

p0250 Several methods are available for patterning thin laminate layers, including photolithography, as discussed earlier. Examples discussed here include the patterning of polymer laminate cards using a laser, particularly a CO_2 laser. Other polymer plastic patterning methods include techniques using a cutting plotter known as xurography and stamp cutting.

s0135 p0255 ***1.12.3.4.2.(i) CO_2 laser cutting*** Laser ablation and laser cutting first became popular in micromachining because structures could be patterned quickly in a substrate from a simple drawing rather than by using traditional micromachining methods such as photolithography. This process can be taken one step further by using a CO_2 or other laser to completely cut through a polymer sheet rather than only remove a portion of it (Verporte and Rooij 2003). CO_2 lasers can operate anywhere between 10 and 400 W but most materials would typically only require 85 to 120 W lasers to cut through the layers of plastics and adhesives common for MEMS dimensions. Laser cutting is also relatively inexpensive; a typical CO_2 laser can be purchased for less than US$10 000 and is very flexible in its patterning abilities. Though laser cutting is a serial process, the lasers can work very quickly and a significant numbers of parts can be generated rapidly.

p0260 The pattern to be etched into the polymer plastic can be drawn in a computer-aided design (CAD) program and input into the translation stage control software of the laser to automate the cutting out and patterning of each polymer layer. This allows for a rapid prototyping setup where fabrication can move from the design stage to the actual patterning and cutting stage within a number of hours. The smallest feature sizes demonstrated using a CO_2 laser in Mylar is about 50 μm; however, 75 μm is the practical limit of the technology and the average dimension of commercial processes are typically 100 μm and higher (b0715 Weigel *et al.* 2001). Laser cutting speeds vary depending on the power of the laser, the speed of the equipment used, and the thickness and material properties of the substrates to be cut. One limitation of CO_2 lasers and laminates is that they primarily melt the polymer film and so a thin ridge of material is often left at the edge of the cut, occasionally making bonding or precise manufacturing difficult.

s0140 p0265 ***1.12.3.4.2.(ii) Other laminate patterning techniques*** As mentioned previously, there are other methods used to cut and pattern polymer laminate cards. Xurography is a method that uses a sharp blade controlled by an automated knife plotter to remove structures from a sheet of polymer plastic (b0045 Bartholomeusz *et al.* 2005). This technology is equally useful for rapid prototyping; however, it is a slower patterning process, which can possibly deform the material at the edge of cuts and does not have such small feature sizes or tolerances. For more information on this technology, refer to Section 1.12.3.5.

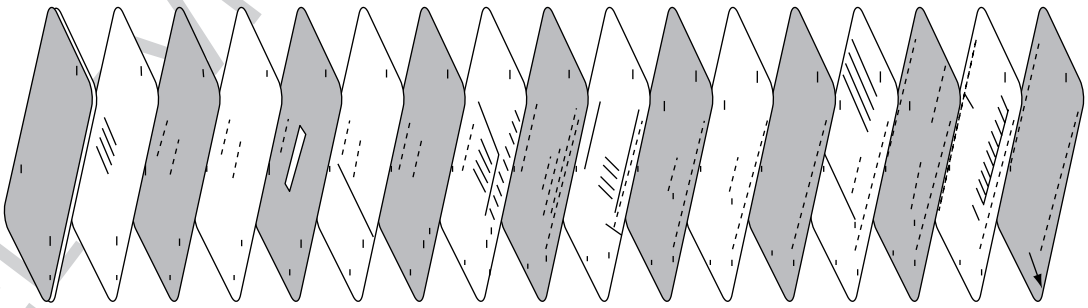
p0270 Another method that is highly practical in mass producing laminate structures is stamp cutting. This can be done by forming sharp cookie cutter type structures to cut out the desired features in the laminate by applying a high pressure. Although stamp cutting is a low-cost method of mass producing layers, it is not as useful for creating quick prototypes and for varying patterns. The possible feature sizes and tolerances using stamp cutting techniques are limited by the stamp's fabrication methods, the material thickness, and the complexity of the design to be cut out. Other methods and materials can be used to fabricate layered microfluidic structures such as powder blasting, molding, and others such as is common in patterning PDMS, SU-8, and dry film photoresists mentioned previously.

s0145 ***1.12.3.4.3 Laminate card assembly***

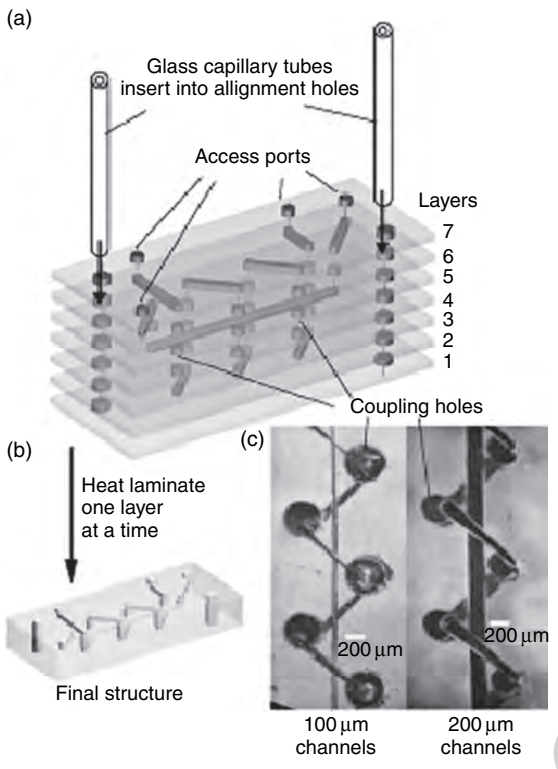
p0275 Each laminate layer that is to be used to produce a 3D microfluidic device or lab card is patterned one at a time. Once the 2D patterns are designed in each layer, the patterned layers are cleaned and the release layers are removed to expose the adhesive. This layer is then brought into contact with another polymer layer and pressure is applied to bond them together. Each polyester layer can vary as to whether or not it will have adhesive coatings on them. Typically, the assembly is alternated with one layer having adhesive on both sides of the polyester sheet and the next layer having a patterned polyester sheet with no adhesive layers on either side, as illustrated in **Figure 8** with the assembly of a 17-layer lab card (Weigl *et al.* 2003). This helps reduce the thickness of adhesive layers between each polymer layer and simplifies purchased material selections. Layers can also be bonded using a thermal bonding process or UV adhesives. Devices fabricated using this technology typically have depth tolerance of less than 1 μm and a width tolerance of about 10 μm. Typical channel dimensions of these devices are 100–3000 μm in width and 50–400 μm in depth (Weigl *et al.* 2001).

p0280 In addition to the design of each layer forming the microfluidic device, numbers and alignment holes are cut out to properly align each card during the assembly stage. The patterned layers are then aligned with each other in their proper sequence, as shown in **Figure 9**. Typical alignment tolerances are in the 1- to 30-μm range depending on how tightly the alignment marks fit with the guide rods. Once the entire 3D device is put together, it is tightly pressed to ensure a sound adhesive bond. In some cases the plain laminate layers can be chemically treated (e.g., with oxygen plasma) to change their wettability, thus modifying the internal surfaces of the channels. Other materials like PDMS or glass can be fabricated and aligned using their typical micromachining processes.

p0285 Not only can 3D lab cards be fabricated from multiple layers of the same material, but hybrid circuit structures and varying materials can be used as well. For example, one or two layers of thin Mylar can be sandwiched between glass slides for added structural integrity or optical properties. Polymers, metals, glass, silicon, and dry stored chemical compounds can be incorporated into the devices during assembly. For example, dry stored reagents and dyes can be stored in small cavities inside the lab card where it can be rehydrated and used during one of its operation steps (Weigl *et al.* 2001). Another example of the added benefit of assembling MEMS devices as laminate layers is that necessary interconnects and packaging components can be inserted between the last and second-to-last layers of the card, eliminating the need of manifolds and adhesive bonds for packaging.



f0040 **Figure 8** Illustration of how 17 layers of patterned Mylar cards are assembled in alternating layers, the light-colored cards have double-sided adhesive on them and the dark-colored cards have no adhesive on them. (Source: Weigl B H, Bardell R L, Schulte T, Battrell F, Hayenga J 2001 Design and rapid prototyping of thin-film laminate-based microfluidic devices. *J. Biomed. Microdevices* **3(4)**, 267–74. ©2001, reproduced with permission from Elsevier.)



f0045 **Figure 9** (a) Each polyester layer is aligned in their proper sequence and small glass capillary tubes or other structures are inserted to keep each layer in alignment. (b) The layers are pressed together and the alignment tubes are removed. (c) A picture of the finished card with dye running through 100 and 200-μm channels for visualization. (Source: Bartholomeusz D A, Boutte R W, Andrade J D 2005 Xurography: Rapid prototyping of microstructures using a cutting plotter. *J. Microelectromech. Syst.* **14(6)**, 1364–74. Figure ©2005, reproduced with permission from IEEE.)

p0290 Because of the speed and simplicity of patterning and assembling Mylar or other plastic laminate layers using a CO_2 laser, complex 3D lab cards can be very quickly assembled from simple 2D layers. The entire process of moving from a CAD design to a complete 3D finished product can take place in less than 4 h, as opposed to days or weeks using other prototyping and fabrication methods. Micronics, a company heavily involved in this technology, uses a class 10 000 clean room facility and is capable of producing over 100 000 laminate devices annually, with an average production of 40 000 new prototype cards per year.

s0150 ***1.12.3.4.4 Applications and examples of laminate technologies***

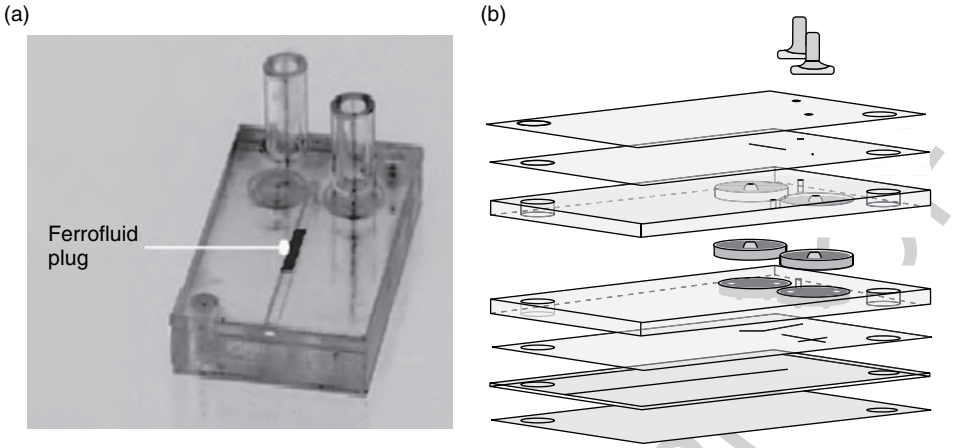
p0295 Laminate methods have been used to create a wide variety of microfluidic devices. Micronics has developed a microcytometer card, a T-sensor card, and an H-filter card (b0715 Weigl *et al.* 2001). The 3D laminate approach has been used to develop devices that enable the analysis of whole blood using 3D fluid control and on-chip sample preparation.

p0300 The ability to easily incorporate hybrid elements into laminate cards allows a variety of applications. Applications for this technology include being able to develop passively driven point-of-care medical diagnostic devices for use in third world countries and remote areas. This can be achieved by incorporating reagents and analysis tools on chips or in hand-held devices. Another example of how hybrid elements can be used in laminate chips includes components to fabricate ferrofluidic micropumps. A ferrofluidic plug is placed inside the chip and combined with valves and externally moving magnets as seen in **Figure 10**, and a small pump is made for pumping highly controllable flow rates (b0775 Yamahata *et al.* 2003).

p0305 Owing to the 3D layout of laminate cards, gravity, absorption, and capillary action can all be used as pumping mechanisms to allow for passively driven microfluidic devices. They can also function as actively driven devices by easily interfacing with manifolds or other devices for portable point-of-care diagnostic devices. Because of the inexpensive nature of the materials used and the rapid fabrication processes achievable using CO_2 laser cutting techniques or stamping, the lab cards are well suited as disposable products and are convenient for research and development applications.

s0155 ***1.12.3.4.5 Limitations of laminate technologies***

p0310 There are several limitations associated with the laminate approach to MEMS and microfluidics. Since a CO_2 laser is being used to cut and pattern each laminate layer, typical laser limitations will still exist. One is that the laser beam can only be focused small, so a limit of about 50 μm to about 75 μm applies to any features. In addition, the use of lasers will cause striations in the sidewalls of the cut material, as noted by Yilbas (1997), as well as bumps next to the cut wall. Striation effects will vary depending on the power of the laser and the speed of the cut; as a general rule, the slower the cutting speed the larger the striation widths. In addition to feature size limits and striation effects, tolerances in the cutting and alignment processes can be problematic. If decent laser patterning equipment and effective alignment techniques are used for patterning and assembly, finished laminate cards can have width tolerances as



f0050 **Figure 10** (a) Photograph of an assembled ferrofluidic micropump constituted of seven layers of polymethylmethacrylate (PMMA), two silicone check valves, and a ferrofluidic plug. (b) Burst view of seven PMMA layers with other microcomponents to form the ferrofluidic pump. (Source: Yamahata C, Chastellain M, Parashar K, Petri A, Hofmann H, Gijs M A M 2005 Plastic micropump with ferrofluidic actuation. *J. Microelectromech. Syst.* **14(1)**, 96–102. Figure © 2005, reproduced with permission from IEEE.)

low as 10 μm and depth tolerances of less than 1 μm (Weigl *et al.* 2001). Limitations on striations, feature sizes, and tolerances can be improved using photopatterned techniques such as SU-8, and dry film photopolymers, but these methods are also slower and more expensive.

p0315 Another inherent limitation of laminate fabrication is the bonding strength and feature spacing limits when bonding layers together. Although different adhesives and bonding methods have their own advantages and disadvantages, the more the number of layers to be assembled together, the more the chance of a bond failure. Other limitations of laminate MEMS include the material properties of the different materials used. Problems such as thermal stability, optical properties, rigidity, strength, sensitivity to light or long-term storage, varying thermal coefficients of expansion and reactivity of the materials with solvents and solutions are also present. In addition, when combining hybrid elements having different material properties, stresses and strains may occur and fabrication times will likely increase.

s0160 *1.12.3.4.6 Summary for laminate technologies*

p0320 Complex 3D lab-on-a-chip cards can be quickly and easily developed by stacking multiple layers of patterned materials. Using laser cutting techniques, each layer can be rapidly patterned without the need of photolithography masks, molds, or other time-consuming techniques. Most polymer plastic materials are suitable for a variety of applications and can be used for fluorescence detection and other optical detection methods due to its transparency. A fabrication setup can be purchased at a relatively low cost and prototyping and fabrication can take place very quickly.

p0325 By taking advantage of 3D structures, passively driven devices can be made to operate by themselves or actively driven devices can be made to interface with other equipment. Hybrid elements and multiple materials can be easily incorporated into the lab cards design without extensive design modifications and time-consuming processes. Surface modifications of the internal laminate layers can be made using chemical treatments such as oxygen plasma treatments.

p0330 Limitations include striation patterns and deformations in laser cut edges, dimensional tolerance of about 10 μm and feature size limits of about 50 μm, material property limitations, adhesive bond limitations, and minimal feature spacing limitations of about 100 μm. The tolerances and minimal design features given, however, are acceptable for most microfluidic applications. In addition, useful devices can be made at a low cost, making them convenient for disposable lab cards and affordable prototyping cards. Overall, this is a fast and affordable method of creating high-performance microfluidic devices made from inexpensive materials suitable for a variety of applications.

1.12.3.5 Xurography

s0165

p0335 Cutting plotters have been used in the graphic design industry for some time, generally cutting designs out

of adhesive-backed materials should be used in creating signs or other artwork. The cuts are made by dragging a knife blade through the material to be used. Once the cuts have been made, the undesired material is peeled away and discarded. A transfer tape is then applied to the top surface of the remaining material so that the design can be moved from its material backing to the desired substrate.

p0340 Many of these cutting plotters have good mechanical resolution with a step size down to 5 μm with some plotters. At the beginning of 2005, Treise *et al.* used a cutting plotter to fabricate planar microfluidic channels by creating the channel design out of a vinyl film using a cutting plotter and sandwiching the channel between a Plexiglas backing, with inlet and outlet holes, and an adhesive covering layer. Later in 2005, Bartholomeusz *et al.* extensively validated this microfabrication process with multiple materials and multiple fabrication techniques. This group found that microfeatures could be fabricated down to linewidths of approximately 20 μm with some materials. They coined this microfabrication method xurography, using the Greek root words *xuron* and *graphe*, which mean razor and writing, respectively. This prototyping method is intriguing because a microdevice prototype can have a very short turnaround time; microdevices can be designed, fabricated, and tested within a working day.

s0170 ### 1.12.3.5.1 Dimensional capabilities of xurography

p0345 The feature sizes obtainable in xurography depend on several factors associated with a cutting plotter. The minimum step size of the cutting plotter, blade sharpness, blade angle, material properties of the substrate, cutting speed, cutting force, and cutting mode are all key factors that determine the smallest features possible and will be discussed in greater detail.

p0350 The minimum step size for cutting plotters is divided into two categories: mechanical resolution and addressable resolution. The mechanical resolution is defined as the smallest step size of the stepper motors and generally ranges from 5 to 25 μm, depending on the machine used. The resolution of the particular cutting plotter helps to define how small the features are that can be achieved. Most of the high-resolution cutting plotters have a mechanical resolution of 5 μm and can range in cost from about US$4000 to US$5000. The addressable resolution is defined as the programmable step size allowed by the software. In general, the smallest step size range that can be output is 10–25 μm.

p0355 The blade size and geometry plays a significant role in the ultimate resolution of xurography. Differing blade thicknesses may be purchased, generally either 0.9 or 1.5 mm. Thicker blades are typically used for thicker materials. The blade sharpness is also a critical factor in deciding final feature sizes. If the blade is dull the material may start to tear, resulting in rougher edges. Also, the thickness of the blade increases at the tip as the blade becomes more dull, which limits the size of features that can be generated (Arcona and Dow 1999)[b0025]. The blade angle also plays a role in feature size. The three most commonly used blade angles are 30°, 45°, and 60°, as measured from the surface being cut to the edge of the blade. These blades range in price from approximately US$15 to US$85 per blade, depending on the manufacturer, angle, and material of the blade. The 45° blade provides a good all-purpose cutting angle. The 30° blade has more of the blade immersed in the material while the 60° blade is minimally in contact with the material being cut, which needs to be taken into consideration when planning for overcut in the design.

p0360 Bartholomeusz *et al.* determined the equations necessary to define what qualities determine the minimum feature sizes capable with xurography and found that the material properties of the substrate being cut play a large role in the minimum feature sizes possible. A thinner, softer material, with low Poisson's ratio and a high shear stress at the adhesive interface, yields the smallest features.

p0365 The cutting plotter settings (cutting speed, cutting force, and cutting mode) are also important in determining minimum feature size. The cutting speed is usually set to the lowest speed, which is 1 cm s^{-1} for most cutting plotters. If the speed is too fast the features will not form well due to tearing and features may possibly be missed when there is a change in direction. It is also important to have the proper cutting force. It should be set high enough so that the material is completely cut but controlled so that the backing of the material is only slightly scored. If the backing is cut too much the blade will become dull, leading to poor device geometry.

p0370 The majority of high-resolution cutting plotters have three cutting modes. The first mode is the drag knife mode, which uses a swivel blade. This mode simply drags the knife through the material and uses the frictional forces to make turns in the cut. This mode can have problems in cutting features that have sharp turns and may break the blade at some turns if the material is hard enough. The second mode is the

true tangential cutting mode, which will cut at corners by lifting the blade completely out of the material, rotating the blade with a motor, then inserting the blade back into the material. This mode can perform overcuts to ensure the material is completely cut and is a good mode for thicker materials. The third mode, the emulated cutting mode, uses a swivel blade as well. However, it will lift the blade just to the top of the material and then pivot to make a turn in the cut and will then be lowered back into the material. This mode helps to protect the blade during turns. Overcuts can be performed with this mode as well, insuring that the material is completely cleaved.

s0175 #### *1.12.3.5.2 Xurography applications*

p0375 Xurography has proven capable of prototyping microfabricated devices by creating either positive or negative features. Prototyping methods have been used in shadow masks, electroplated microchannels, micromolding (MM), and laminated microfluidic structures; another group more recently developed a variation on laminates, producing microchannels using a double-layer adhesive material. These applications will be discussed in greater detail.

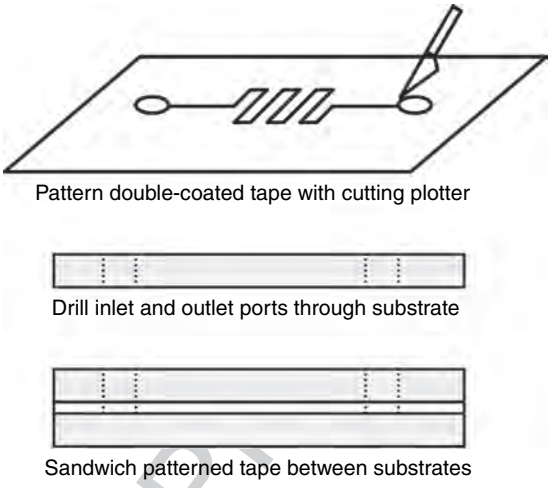
p0380 Electroplated microchannels take advantage of Rubylith® material as a sacrificial layer. The material is patterned with the cutting plotter and the undesired material is peeled away. This pattern is then transferred to a substrate, which then undergoes sputtering of a titanium seed layer followed by a gold seed layer. The substrate channel ends are covered in Kapton tape, in order to prevent the inlets of the channel from being coated in metal, and then placed in an electroplating bath, depositing nickel onto the gold seed layer. Once the nickel metal is deposited, the Rubylith® is then dissolved with acetone, leaving hollow nickel channels behind.

p0385 MM over a xurography-created pattern can be done by creating positive features with a cutting plotter out of a thermal laminate or an adhesive-backed material. This material is then transferred and adhered to a dish that PDMS can be poured into, thus creating a mold. The dish and features are covered with a silane coating to prevent the PDMS from sticking to the mold. PDMS is then poured into the dish, degassed in a vacuum chamber, and cured in an oven. Once cured the PDMS is peeled from the mold, leaving microfeatures in the PDMS (Kim and Gale 2005).

b0370

p0390 Laminated microfluidic structures can be used to create 3D prototypes. This is done by cutting parts of the channel and access ports on single slices, with alignment holes cut on opposing corners of each layer. Several of these layers can be stacked together, aligned by sticking glass capillary tubes through the alignment holes, and then adhered together by applying heat and pressure (Bartholomeusz *et al.* 2005).

b0045



f0055 **Figure 11** Microchannel fabrication process using a double-coated tape. The double-coated tape is patterned with the cutting plotter and the undesired material is peeled away. Holes are then drilled through a substrate to create inlet/outlet ports for the microchannel assembly. Lastly, the patterned double-coated tape is sandwiched between two substrates, one that has been drilled and one that has not, to seal the microchannel. (Source: Bartholomeusz D A, Boutte R W, Andrade J D 2005 Xurography: Rapid prototyping of microstructures using a cutting plotter. *J. Microelectromech. Syst.* **14(6)**, 1364–74. © 2005, reproduced with permission from IEEE.)

p0395 A double-layer adhesive material patterned with a cutting plotter and sandwiched between two subtrates for channel fabrication has been used as a very quick and simple method for microfluidics. This method involves cutting the desired channel dimensions and inlet/outlet ports out of a double-layer adhesive material using the cutting plotter. One of the substrates to be used has holes drilled at the inlet and outlet port locations for access to the channel. The double-layer adhesive material is then sandwiched between the two substrates, thus creating a microchannel (Sundberg *et al.* 2006). **Figure 11** shows the fabrication process for these microchannels.

b0655

1.12.4 Low-Cost Methods for Rapid Prototyping

s0180

p0400 In many instances, low-cost, proof-of-concept devices are the objective and more expensive techniques for further prototyping or mass production can be used

later if concepts can be demonstrated early on. Traditional MEMS methods can be extremely slow and expensive for prototyping due to the high fixed costs associated with the tooling and the difficulties in developing new processes on these tools. Outsourcing using traditional MEMS tools, which may be more cost-effective, usually has lead times of 6 months or more, which can be problematic as new concepts are being explored and there is the risk of failure in early attempts. Thus, a range of rapid prototyping techniques for MEMS devices have been developed to provide proof-of-concept before the more expensive and slow processes are applied. Note that most of these rapid, inexpensive processes are designed to implement mechanical functions, as most electrical processes are best implemented in traditional silicon and best prototyped using computer simulations.

p0405 One of the best processes for rapid prototyping in MEMS and microfluidics applications is soft lithography, which is discussed at length in its myriad forms. Other techniques for inexpensive rapid prototyping include powder blasting, photopatternable polymers (Section 1.12.2.2.1), xurography (Section 1.12.3.5), and laminate technologies (Section 1.12.3.3), the latter three have already been discussed.

s0185 1.12.4.1 Soft Lithography

p0410 Soft lithography involves the use of soft polymers that are molded over molds typically produced using photolithography. The earliest version of soft lithography, μCP (b0740 Xia and Whitesides 1998), then allows for that pattern to be replicated many times by stamping materials onto a substrate (thus the term soft lithography, b0740 Xia and Whitesides 1998, b0745 Xia *et al.* 1999). In more advanced versions of soft lithography, the molded polymers can be used as mechanical devices, most typically in microfluidics. A number of other variations of soft lithography have developed, and each will be discussed. The major advantage of soft lithography is the simplicity of the process that makes it easy for the chemist, biologist, and material scientist who want to apply these advances to their own research. The fabrication processes used to create plastic devices using soft lithography are based on replication (casting, embossing, or injection molding) and are faster and less expensive than those used on glass and silicon. The low cost of both the raw materials and the processes associated with soft lithography allows the production of potentially disposable devices. The soft polymers used with soft lithography tend to produce devices that are robust and easy to handle, which is not the case with glass and silicon microdevices. Soft lithography is also applicable to nonplanar surfaces and 3D microsystems, which is typically not the case with more traditional microfabrication techniques (b0245 Gates 2004, b0740 Xia and Whitesides 1998).

With polymers, researchers have been able to p0415 fabricate high-quality microsystems, even those on the nanoscale. We call these unconventional fabrications softlithography due to the use of a soft material and the ability to generate micropattens.

Generally, the soft lithography procedure starts p0420 by making a mold structure based on the initial idea using traditional lithography or other methods. A soft polymer is then poured over the mold and cured to produce a polymer part. The most commonly used polymer in soft lithography is PDMS as it has a number of useful properties such as reasonable strength, optical clarity, and short cure times; moreover, it has the capability of conforming to even nanoscale patterns (b0575 Roger and Nuzza 2005). Usually soft lithography is organized into two categories depending on the pattern transfer method: MM and μCP. MM includes replica molding (RM), microtransfer molding (μTM), micromolding in capillaries (MIMIC), and solvent-assisted micromolding (SAMIM). μCP is used for elastomeric stamping in order to transfer the pattern onto a substrate (b0245 Gates 2004, b0740 Xia and Whitesides 1998, b0745 Xia *et al.* 1999). In this section, the main elements of soft lithography and the primary methods of soft lithography are introduced along with a review of recent applications.

1.12.4.1.1 Material for soft lithography s0190

Soft lithography relies on soft polymers that are p0425 appropriate for stamping, molding, and embossing. Those polymers that have a low interfacial energy, that are chemically inert, that have a high thermal stability, and that are easily modified appear to be the best candidates. Many research groups have explored a variety of materials for soft lithography including materials such as polyimide, polyurethanes, Novolactm™ resins, and PDMS, which is the most commonly used.

1.12.4.1.1.(i) PDMS material properties PDMS s0195 p0430 has several useful material properties for stamping and molding. It provides a surface that has a low interfacial free energy, is chemically inert, has good gas permeability and good thermal stability, and is

optically transparent. The surface properties of PDMS are also relatively easy to modify. The commercially available PDMS most commonly used is Sylgard™ 184 produced by Dow Corning. It consists of two parts – a silicon base and a curing agent. For basic soft lithography, the base and the curing agent are mixed well and poured over the master mold. To remove the bubbles in the liquid-state PDMS, the mold with the liquid PDMS is put into a vacuum chamber until the bubbles are completely removed. The PDMS can then be cured at room temperature (~2 days) or at elevated temperatures (a few hours). The physical properties of Sylgard™ 184-PDMS include a high tensile modulus (1.8 MPa) and high physical toughness (4.77 MPa), low shrinkage after curing (1.1%), and high elongation (160%). PDMS also has a low free surface energy ($\gamma = 21.6\,\mathrm{dyn\,cm^{-2}}$) that makes it possible to release the PDMS structures easily from the mold. The low thermal conductivity ($k = 0.2\,\mathrm{W\,m^{-1}\,K^{-1}}$) allows PDMS to be used as a thermal isolation material. PDMS has a thermal expansion coefficient of $310\,\mu\mathrm{m\,m^{-1}\,°C^{-1}}$ and is thermally stable below 150 °C. (b0140 Clarson and Semlyen 1993, b0190 Dow Corning Co. 2005, b0490 McDonald and Whitesides 2002).

p0435 The gas permeability of PDMS and the impermeability of PDMS to liquids are also useful characteristics for some chemical applications, especially in microfluidics. For example, a unique gas permeation pump has been developed by using these properties (Eddings and Gale 2006). PDMS also has good biocompatibility properties and it is possible to implant within the body and to make the cell culture chips because of its nontoxic properties (b0210 El-Ali *et al.* 2006).

p0440 The fabrication of nanoscale features has to be performed carefully with PDMS. One reason is the difference in the thermal expansion coefficient between the PDMS and the mold. This difference can cause distortion of the replicated features. The other reason for distortion is shrinkage during the curing of the prepolymer. To combat these drawbacks during the fabrication of nanoscale features, no solvent evaporation can occur and a low-temperature curing environment needs to be used. During the peel-off step (removal from the mold), distortion of fabricated structures may also occur. Also, for μCP, the stamping feature needs to have high mechanical stability to prevent the collapse of the feature, so it is important to consider the stamping geometry. To overcome these potential problems, different versions of PDMS have been developed including harder PDMS and UV-curable PDMS. With these modified PDMS, features, aspect ratios >4:1 are possible without collapsing (Quake *et al.* 2000, b0575 Roger and Nuzzo 2005).

1.12.4.1.1.(ii) Surface modification of PDMS s0200

p0445 While the bulk properties of PDMS make it generally useful, the surface properties of PDMS are often difficult to control and pose challenges when working with many liquids and proteins. PDMS is strongly hydrophobic, which can make filling reservoirs difficult and can cause channels holding aqueous solutions to collect bubbles since the solutions dewet from the surface. PDMS structures can also become distorted when they contact organic solvents and hydrophobic analytes. The low surface energy of PDMS also makes it difficult to deposit other materials on PDMS (though PDMS does bond well to itself). For applications that need surface electrodes to produce an electric field, such as in capillary electrophoresis (CE), in electrochromatography, and in electroosmotic pumps, electrode deposition can be problematic. The PDMS surface is also highly active in that the molecules at the surface are continuously being replaced by PDMS in the bulk, making long-term control of PDMS surface properties difficult. To overcome some of these challenges, several techniques for modifying the surface of PDMS structures have been developed.

p0450 The surface of PDMS is highly inert; therefore, surface modification can be difficult to achieve. Nevertheless, several surface coating approaches have been developed including plasma, covalent, and dynamic modification methods.

p0455 Oxygen plasmas, which are composed of ionized oxygen at high energy, have been used to create hydrophilic PDMS surface through oxidation. Oxygen plasma can be used to form silanol groups (–OH) at the end of methyl groups ($-CH_3$). As the silanol groups are polar, the treated surface is easily wettable with polar solvents. This method is commonly used to treat the surface of PDMS because the process can be completed in only a few minutes, it does not require the use of chemicals, and it has good repeatability and consistency. With this treatment, PDMS can be used to implement the electroosmotic flow and bonding between molded PDMS and flat PDMS/glass. Unfortunately though, oxygen plasma treatments cannot be used for microsystems that require long-term stability. Usually, the plasma treatment is effective for less than 3 h in the

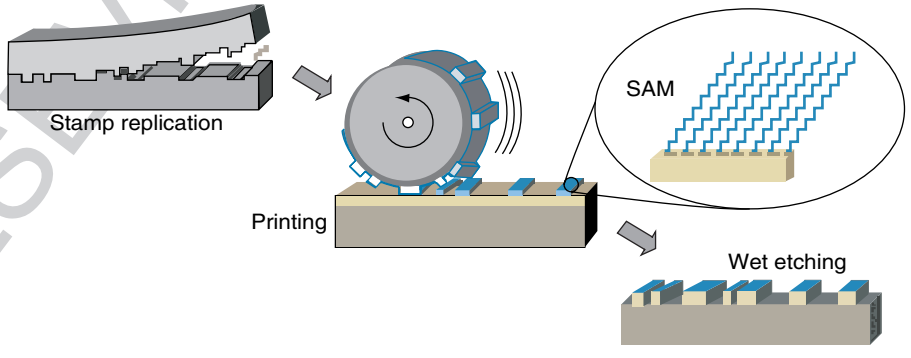
presence of aqueous solutions (Duffy *et al.* 1998, Makamba *et al.* 2003).

p0460 To overcome the mobility of the surface in PDMS, static coating, such as by covalently linking ionizable molecules to PDMS monomers on the surface, was developed for permanent PDMS surface modification. To bind these ionic polymers to PDMS, UV graft polymerization, silanization, or CVD is usually used. UV graft polymerization is used to create reactive sites (radicals) on the PDMS surface, which otherwise has no functional group on the surface. UV or ionizing radiation can generate free radicals that can be used as the initiation site for a polymeric chain on the surface of PDMS. UV graft polymerization has been shown to produce stable surface properties and is relatively easy to perform; the surface polymers have low penetration into the bulk PDMS. Silanization has been used to make an immobilized polyethylene glycol (PEG) layer on the surface of PDMS. Before stacking the PEG layer on the PDMS, the PDMS surface is oxidized in oxygen plasma and immersed into Si–PEG–Si solution. This technique is usually used to inhibit protein adsorption on the surface of PDMS. CVD can be used to deposit thin films of various materials and can also be used to modify the surface of PDMS. This approach was used to deposit reactive coatings of poly(*p*-xylylene carboxylic acid pentafluorophenolester-co-*p*-xylylene) (PPX-PPF) and poly(*p*-xylylene-2,3-dicarboxylic acid anhydride). Without the need for further activation, the high chemical reactivity of these functional groups supported conversion with biological ligands or proteins and was used for surface patterning of PDMS using μCP (Barbier *et al.* 2006, Hu *et al.* 2002, 2003, Lahann *et al.* 2003, Slentz *et al.* 2002, Xia *et al.* 2004). Another surface modification method is the use of a surfactant, which has a hydrophobic tail that can adsorb to the hydrophobic PDMS surfaces easily. This hydrophobic tail interacts strongly with the PDMS, while the charged head stretches out of the surface and changes the surface charge density. Neutral poly(oxyethylene)-based surfactants and cationic surfactants are usually used to modify the surface of PDMS (Badal *et al.* 2002).

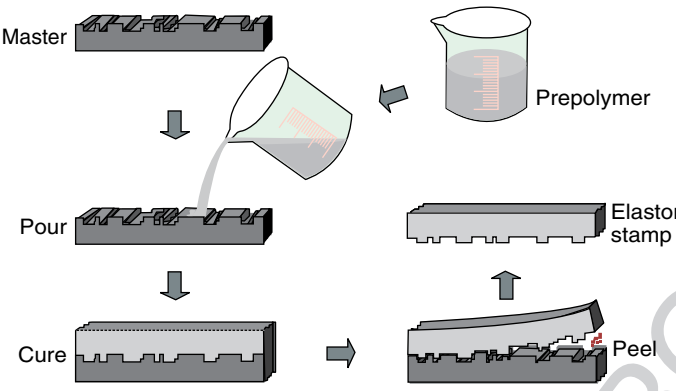
1.12.4.1.2 Microcontact printing s0205

μCP is the most important patterning technique p0465 among the soft lithography methods. In μCP printing, like in conventional printing techniques, the patterned stamp is brought into contact with a substrate to transfer an ink, a solution of an alkanethiol, or other molecules to a surface modified substrate and create patterns on the substrate, as shown in **Figure 12**. The technique was developed to deposit arrays of self-assembled monolayers (SAMs) within a few seconds (Jackman *et al.* 1995). A precisely arranged monolayer builds up rapidly at the area of contact (Gates 2004, Xia and Whitesides 1998, Xia *et al.* 1999). μCP of SAMs on a substrate as a resist layer or protective layer from etchants has been demonstrated as a rapid photolithography replacement technique (Geissler *et al.* 2002). Bernard *et al.* (1998) were able to pattern distinct regions of antibodies and other proteins on polystyrene substrates for further use in binding assays.

p0470 Because of the complexity of working with biomolecules, several considerations must be understood when selecting the solution to be patterned. Biomolecule solutions that will not contribute to PDMS swelling should be employed to retain the patterned resolution on the molded PDMS stamp head. Solvents that will diffuse or that have a high affinity for PDMS rather than the substrate should also be avoided to promote uniform, concentrated



f0060 **Figure 12** The microcontact printing procedure with an elastomeric stamp. SAM, self-assembled monolayer. (Source: http://www.research.philips.com/technologies; reproduced with permission.)



f0065 **Figure 13** The stamp replication process. After curing the polymer, the elastomeric stamp is peeled off the master and uses the master for microcontact printing. (Source: http://www.research.philips.com/technologies; reproduced with permission.)

printing. Other important criteria include low vapor pressures at ambient conditions and narrow diffusion characteristics, which will assist in printing resolution and biomolecule stability (b0160 Delamarche *et al.* 2003).

p0475 The stamp for μCP is usually made from an elastomeric polymer PDMS. This material allows for conformal contact with the substrate combined with advantageous chemical and physical properties important for the molecule transfer behavior. Stamps are fabricated by casting prepolymers on a master with a negative of the desired pattern, curing it, and peeling the cured stamp off the master as shown in **Figure 13**. Depending on the stamping method, the technique is referred to as planar stamping or rolling stamping. One particular advantage of μCP is its ability to print on nonplanar surfaces with a modified planar stamp (b0340 Jackman *et al.* 1995). In roller stamping, altering the configuration slightly by curving the PDMS stamp can also achieve unique circular patterns (b0230 Franssila 2004).

p0480 The resolution of μCP is generally as good as the method used to make the mold, since μCP can replicate even nanoscale features. Recently, the resolution of μCP has been improved by solving problems such as surface diffusion, disorder at the edges of the printed SAMs, and the isotropic nature of many of the etching and deposition methods. These problems are eliminated by the use of what is called nanotransfer printing (nTP). In nTP the SAMs are used as covalent glues and release layers for transferring material from relief features on a stamp to a substrate. This approach is a purely additive technique that can generate complex patterns of single or multiple layers of functional materials with nanometer resolution over large areas in a single process step (b0435 Loo *et al.* 2002a, b0440 b).

p0485 An interesting development in μCP is to use PDMS itself as the ink material. This method, which is referred to as decal-transfer printing, utilizes a PDMS stamp to transfer other structures (such as membranes) made of PDMS. Coating the handle PDMS stamp with an organic material aids the release of the carried structures (b0120 Childs and Nuzzo 2002, b0125 Childs *et al.* 2005).

p0490 μCP can be used to pattern other microdevices. μCP has been used to make a charge pattern on thin electrets (e.g., polymethylmethacrylate (PMMA)). This technique can pattern regions of charge with lateral dimensions down to at least 100 nm (b0345 Jacobs and Whitesides 2001). μCP can be used to make patterns within microchannels as well. For example, selective adsorption of fibronectin and bovine serum albumin onto the patterned microfluidic channels and the deposition of various proteins within multiple patterns using laminar flow have been accomplished using μCP (b0365 Khademhosseini *et al.* 2004). Dozens of other applications of μCP and related techniques have been outlined in other review articles (b0245 Gates *et al.* 2004).

1.12.4.1.3 Micromolding with soft lithography s0210

p0495 Several variations of MM using soft lithography exist including RM, μTM, MM in capillaries, and solvent-assisted MM.

1.12.4.1.3.(i) Replica micromolding s0215 p0500 MM is used to create useful structures in the soft polymers associated with soft lithography. The molds are then sometimes used to create structures in other materials. To create the PDMS mold or structures, any micromaching technology can be used to construct the pattern, but traditional silicon etching is often used. After making the original mold out of silicon or any other material, the surfaces of the patterned silicon

must be coated with silane to allow easy separation between PDMS and the patterned silicon. The prepolymer is coated on the patterned silicon and then polymerized. After curing the prepolymer, the polymer is peeled off from the master and can be used for further processing steps or used directly.

p0505 SU-8 is also used regularly to make master replica molds for PDMS molding (Mata *et al.* 2006). More information on using SU-8 to make these molds is available in Section 1.12.2.2.1.(ii). After completion of the SU-8 lithography, the SU-8 master mold has to be coated with silane to allow the molded polymer to peel off easily after curing. The prepolymer can then be cast over the SU-8 master, cured, and released. This approach has been used to produce structures under 100 nm in size.

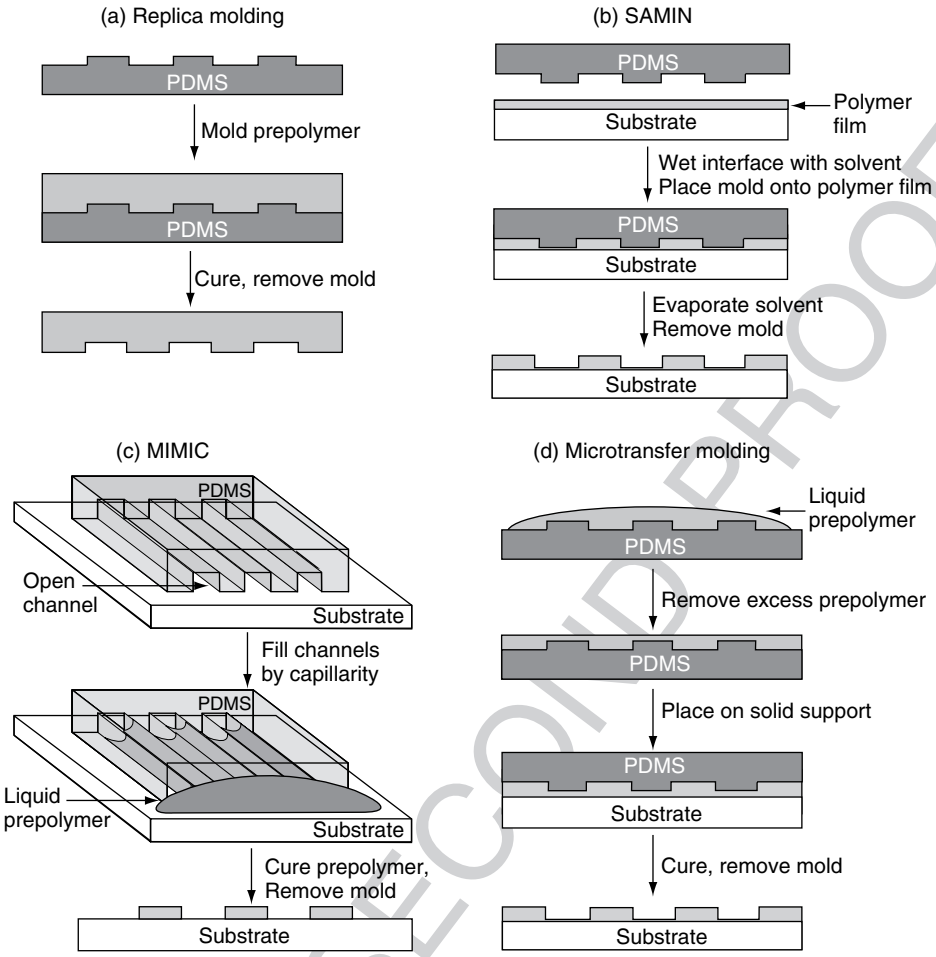
p0510 Once a polymer (PDMS) mold has been generated, it can then be used to produce multiple copies of the original mold. The PDMS mold can be used to make multiple PDMS copies or other materials can be used. Generally, the prepolymer is not able to penetrate into PDMS and each PDMS mold can be used about 20 times before the molds begin to fail (Gates 2004). Using the RM method, it is possible to make copy nanostructures with high resolution (even copying a protein structure on the surface of the mold). For example, structures as small as 1.5 nm were replicated with a PDMS mold (Gates and Whiteside 2003). To accomplish this feat in a practical way, the feature is fabricated with a focused electron beam in PMMA and replicated in a PDMS mold. Then, polyurethane (PU) can be used to replicate the original structure using the PDMS mold. Thus, this method can replicate nanopatterns over large areas rapidly and at low cost.

p0515 s0220 ***1.12.4.1.3.(ii) Microtransfer molding*** In μTM, the elastomeric mold is filled with a polymer precursor, and the excess prepolymer is removed (**Figure 14**). The soft mold is pushed up against a substrate, the patterned feature in the soft stamp is cured while in contact with the substrate by appropriate ways, and the stamp is peeled off. By repeating this procedure, a multilayer structure can be created on a single substrate.

p0520 Compared with μCP, μTM can produce thick and multiple layers easily. But, μTM requires the use of a viscous prepolymer that consumes more time for curing and for filling the capillaries of the patterns. To speed up the process, hydrophobic dendrimers (G4 aldehyde, CHO end group) can be used to fill the capillaries of the stamp within 30 s. By controlling the concentration of dendrimers in the solution inking the PDMS stamp, minimum feature sizes of 40 nm can be achieved (Thibault *et al.* 2006). The creation of 3D structures can also be completed in a single molding step called membrane-assisted μTM. In this process, a technique such as multiphoton absorption polymerization is used to create a master structure that has closed loops that are interrupted by thin membranes. After creating the loop structure with the MAP technique, the mold is immersed in PDMS to make the mold for μTM. The PDMS is cured and the PDMS mold is peeled off from the substrate. The PDMS mold is filled with molding material and the pattern is transferred to a substrate. While the PDMS mold contacts the substrate, the material being molded is cured and the mold is removed (LaFratta *et al.* 2006).

1.12.4.1.3.(iii) Micromolding in capillaries In s0225 p0525 MIMIC, a soft mold like those made with PDMS is contacted with the surface of a substrate to form a network of open microchannels (**Figure 14**). The soft stamp is pressed onto the substrate evenly and a prepolymer is applied to access holes in the mold. This process can be vacuum assisted to speed flow into the holes. The prepolymer flows into the cavities formed by the soft mold on the substrate and fills the cavities automatically due to capillary forces. After curing and peeling it from the soft mold, the polymer structure remains on the surface of substrate. For long capillaries, the rate of filling decreases significantly owing to the viscous drag of the fluid in the capillary and the distance over which the fluid has to be transported, which should be considered during the design phase. The rate of filling also decreases as the cross-sectional dimension of the capillary decreases and as the interfacial free energy of the surface decreases (Gates 2004, Xia and Whitesides 1998, Xia *et al.* 2003). Recently, a preceramic polymer that is transparent, solvent-resistant, thermally stable, and biocompatible was fabricated using MIMIC. Transparent poly(silazane) glass-derived microchannels and structures can be fabricated based on this technique. The structures may be useful in the field of micro-total-analysis systems (Asthana *et al.* 2006).

1.12.4.1.3.(iv) Solvent-assisted micromolding s0230 p0530 SAMIN combines RM and embossing concepts simultaneously. SAMIN uses an elastomeric PDMS mold in combination with an appropriate solvent (**Figure 14**) – instead of a rigid mold and high temperatures and pressures – to emboss the polymer.



f0070 **Figure 14** A schematic of four different micromolding techniques. (Source: Gates B D, Xu Q, Love J C, Wolfe D B, Whitesides G W 2004 Unconventional nanofabrication. *Annu. Rev. Mater. Res.* **34**, 339–72. © 2004, reproduced with permission from Annual Reviews, www.annualreviews.org.)

The solvent is either applied to the PDMS mold or retained in the polymer film before placing the two surfaces in contact. A small amount of solvent is dispensed on a patterned PDMS stamp and the stamp is placed on the polymer to be molded. The solvent causes swelling in the polymer and causes expansion of the polymer into the patterns of the stamp. The gas-permeable mold prevents trapping of air pockets and nonuniform solvent evaporation. The mold is then removed to reveal a relief structure complementary to the topography of the mold. For this technique, the wetting of the PDMS mold by the solvent and conformal contact between the PDMS mold and the substrate are the most important factors for successful fabrication (b0245 Gates 2004). The application of SAMIN to nanoscale features has been limited primarily by the lack of appropriate masters rather than by the fundamental characteristics of this process. To overcome this limitation, composite elastomeric mold like hard PDMS can be used to make smaller features (~20 nm) (b0530 Odom *et al.* 2002).

p0535 A limitation of elastomeric PDMS mold is that swelling may occur when PDMS is used with organic solvents. This swelling causes distortion of the pattern in soft lithography and may lead to pattern collapse in the mold. Surface modification of the PDMS mold with poly(urethaneacrylate) has been shown to reduce the rate of solvent absorption into PDMS (b0425 Lee *et al.* 2006).

1.12.4.1.4 Packaging of components fabricated using soft lithography s0235

p0540 In microfabrication, packaging is defined as all the integration and connection steps after fabrication of the fundamental device is complete. It includes postprocessing release, package/substrate fabrication,

assembly, testing, and reliability assurance. The package provides functional interfaces between microdevices and the environment (Lee *et al.* 2003). These interfaces are directly related to the application. Thus, unique packaging approaches have been developed for use with soft lithography.

p0545 s0240 ***1.12.4.1.4.(i) Bonding*** One of the most basic packaging steps is bonding. Two PDMS substrates can be bonded to each other using a variety of techniques. The most common technique for bonding PDMS substrates is the use of an oxygen plasma to oxidize the surface followed by rapidly placing the two substrates in contact with one another. The seal between the two pieces of PDMS can be sufficiently strong such that the two substrates cannot be peeled apart without failure in the bulk PDMS. The bond strength has been found to be highly dependent on the measured contact angle of the PDMS after exposure to the oxygen plasma. The lower the contact angle, the better the bond (Xie *et al.* 2005). As a result, a contact angle below 5° provides a good bond strength (Bhattacharya *et al.* 2005). An identical process can be used to bond PDMS to glass substrates.

p0550 Several other methods for bonding PDMS are available. For example, placing two partially cured substrates (or even if only one is partially cured) in contact before final curing results in a good bond strength between PDMS substrates. These films of uncured PDMS can also be placed between layers of cured PDMS to produce a high-quality bond.

p0555 Rigid polymers like PMMA are often used in making rigid molds or stamping structures for soft lithography. To package micro- or nanofabricated structures with PMMA, thermal bonding, lamination, adhesives and solvent-assisted bonding are usually used. Surface modification such as air plasma treatment, hydrolysis and aminolysis are also available to assist in developing strong bonds. A comparison of techniques and a determination of the optimal methods for bonding PMMA without damage to the microstructures is available (Brown *et al.* 2006).

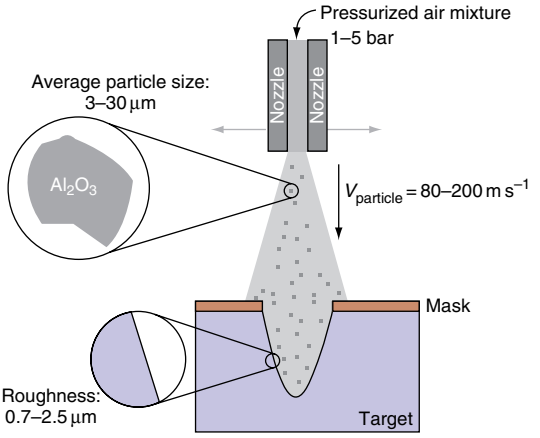
p0560 s0245 ***1.12.4.1.4.(ii) Microfluidic packaging*** In microfluidic systems made by RM, the channel inlets and outlets often need to be connected to pumps or other fluid components. Several methods have been used to accomplish this task. The most basic are glued interfaces, where connecting tubing is attached with an adhesive (often PDMS) to the channels. One method for use with SU-8 master molds requires that an inlet and an outlet post structure be created after fabrication of the microchannel structure on the silicon wafer. Essentially, the packaging channels are molded into the PDMS. With this mold, the PDMS replica can be peeled off and connections with a syringe needle can be made. Usually, oxygen-reactive ion etching and epoxy bonding are used to bond PDMS interconnects to various substrate materials such as glass, silicon, and other polymers (Li 2003).

p0565 A second method for creating a packaging channel is to use a coring tool. In this case, a channel is cored from the surface to the buried microchannel and a syringe needle is inserted into the hole and a press fit is used to keep the channel sealed. The use of a needle that has a larger diameter than the coring tool leads to a good fit and a good seal within the microfluidic structure (Christensen *et al.* 2005). Using this concept of an interference fit, seals designed for various pressures were fabricated and tested for leakage and internal wear due to repeated insertion of a tube. The sealing pressure is a function of the contact pressure in each design due to the low stiffness of PDMS. On the basis of this result, guidelines can be set for selecting the appropriate sealing method and for modeling more complex captive connectors (Friedrich *et al.* 2005).

1.12.4.2 Powder Blasting s0250

p0570 Abrasive blasting or sand blasting is a widely used material removal process. The microfabrication version, typically called powder blasting, has been demonstrated as a viable, low-cost option for the fabrication of MEMS and microfluidic devices, especially for brittle materials (**Figure 15**). The resolution possible for powder blasting is reduced by the size of the particles, which typically range from 10 to 50 μm and the complexity of the mask patterning undertaken. However, a high etch rate and no clean room requirement make powder blasting an attractive alternative to standard wet and dry etching techniques. These advantages make powder blasting an ideal candidate for rapid prototyping applications.

p0575 Powder blasting utilizes a pressurized air beam containing ceramic particles such as Al_2O_3 to create 3D microstructures. By adjusting and controlling parameters such as the beam pressure, beam diameter, beam–substrate separation distance, beam angle of incidence, mask pattern, and mask undercetching, novel 3D features are possible (Belloy *et al.* 2000, 2001, Slikkerveer *et al.* 2000). Masking for the



f0075 **Figure 15** A schematic of the powder blasting process using Al_2O_3 as the blasting particle. (Source: Wensink H, Jansen H V, Berenschot J W, Elwenspoek M C 2000 Mask materials for powder blasting. *J. Micromech. Microeng.* **10**, 175–80; reproduced with permission from the Institute of Physics.)

powder blasting process consists of an etch-resistant coating such as a polymer that is patterned on top of the substrate. Pawlowski *et al.* demonstrated the use of PDMS/SU-8 polymers for an etch mask. PDMS was found to have an etch rate 15 times smaller than glass, allowing for high mask integrity in the course of experiments. With the patterning and etch-resistant capabilities of the PDMS/SU-8 combination, 30-μm structures were reported (Pawlowski *et al.* 2005).

s0255 1.12.5 Low-Cost Methods for Volume Manufacturing of MEMS

p0580 In many cases, traditional MEMS technologies can be used to produce inexpensive microdevices since the fixed costs associated with the expensive tools can be spread over a large number of devices. For example, precision MEMS accelerometers for use with car airbags can sell for less than US$2 each. For volumes that do not reach millions of parts per year, and for devices that are not easily fabricated using traditional techniques, molding and embossing techniques are the most cost-effective for mass production. Several of these techniques will be reviewed for their application to microdevices.

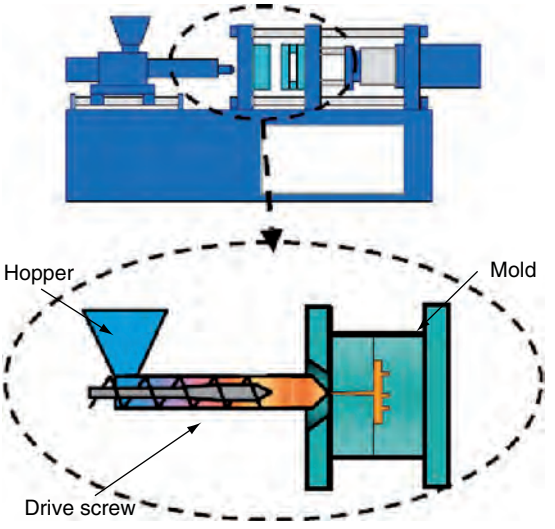
s0260 1.12.5.1 Injection Molding

p0585 The utilization of injection molding has made possible the mass production of polymer components for various industries. The extension of injection molding to MEMS and microfluidic components is helping to develop academic and commercial devices without the need of costly MEMS foundry facilities. Injection molding offers solutions such as low cost (for large volumes), high tolerances, and fully automated production. The limitations for injection molding are often high tooling costs (for small volumes), shrinkage, and partial mold filling. These limitations are often exacerbated for microscale components as even tighter tolerances are required for mold inserts, shrinkage, and mold filling. For microscale applications, mold inserts are often fabricated by high-precision laser ablation, lithography, EDM, or other costly micromachining techniques that may cost more than the injection molding equipment. However, recent discoveries at the academic and commercial level have begun to address some of the obstacles that have deterred the use of injection molding for microsystems.

1.12.5.1.1 Process overview

s0265 p0590 The injection molding process generally encompasses four basic steps: melting, injection, cooling, and ejection of the finished part. The entire cycle time will vary from seconds to minutes, based on the polymer, part size, mold complexity, and equipment used. While there are a considerable number of different injection molding machines, they all consist of three major components: the injection unit, the mold cavity, and the clamping unit.

p0595 The typical injection unit consists of three basic components: a hopper, a heated barrel, and reciprocating screw, as shown in **Figure 16**. Polymer in the form of pellets is forced through the hopper into the heated barrel, where the temperature of the polymer is raised above its melting point. A shear force is then applied by the reciprocating screw, which contributes to polymer melting through viscous heating. Polymer flow is also improved by shear thinning that occurs in the melted polymer. At this stage, the reciprocating screw is driven forward by a hydraulic drive, injecting the molten polymer into the mold cavity, which forms the shape of the desired component. A mechanical or hydraulic clamping unit opposes the force of the injection, holding the mold plates together. Backward polymer flow is prevented from returning to the barrel cavity by a nonreturn valve that sits at the tip of the reciprocating screw. The mold is allowed to cool, allowing the polymer to solidify. The mold is then opened and the part is ejected from the mold. After the mold cycle is



f0080 **Figure 16** A schematic of a typical injection molding machine showing the hopper, drive screw, and mold. (Source: Becker H, Heim U 2000 Hot embossing as a method for the fabrication of polymer high aspect ratio structures. *Sens. Actuators* **83(1)**, 130–5. © 2000, reproduced with permission from Elsevier.)

completed, the screw retracts and the process is repeated (Bryce 1996).

s0270 ***1.12.5.1.2 Microscale injection molding***

p0600 Standard injection molding processes require slight modifications when microscale components are fabricated. Microscale injection molding processes focus on the release of delicate microstructures from the mold and proper mold filling in microcavities. Mold release agents are generally used to assist in component release from the mold cavity; however, for certain applications the mold release may adversely affect device biocompatibility. To circumvent this step, the mold cavity walls are given a slight incline, provided the incline is acceptable in the final part. If vertical sidewalls are required, special care must be taken to reduce the effects of friction that may hinder the smooth release of the components from the cavity (b0300 Heckele and Schomburg 2004). It has been reported that an average surface roughness value of less than 300 nm will work for most low aspect ratio applications. To ensure proper release for high aspect ratios features (>5) a surface roughness of less than 100 nm is necessary (b0560 Pfleging *et al.* 2003).

p0605 Complete mold filling is critical for the success of microscale injection molding. A typical strategy for proper filling of the mold is to evacuate and heat the mold cavity. Compression effects (also known as diesel effects) in mold filling, where compressed air is trapped in blind corners and polymer surfaces are burned, provide a unique challenge when optimizing an injection molding process. Evacuation of the mold cavity is an effective strategy designed to remove regions of trapped air that may leave voids in the final polymer component. Another strategy imposed to improve mold filling is heating of the mold cavity. Because of the large surface area-to-volume ratio typical in microscale components such as microchannels, a rapid equilibration temperature occurs between the molded polymer and the temperature of the mold. The equilibrium change in temperature for microscale injection molding has been found to be up to two orders of magnitude faster than conventional molding (b0730 Whiteside *et al.* 2005).

p0610 The optimization of injection molding parameters and processes is often based on operator experience and trial and error. However, recent modeling tools have been developed by companies and researchers to provide computer simulations of the filling process (b0785 Yao and Kim 2002). Moldflow Corporation has developed a commercial tool specifically for microscale flow analysis, referred to as Micro Moldflow Analysis™. The implementation of these simulation tools will help speed up the injection molding parameter selection stage, while simultaneously reducing injection molding cost and operator time.

s0275 ***1.12.5.1.3 Microscale applications of injection molding***

p0615 As academic research does not generally require high-volume production of polymer components, most injection molding research remains unreported in commercial production settings. However, some recent novel attempts have been reported for microfluidic injection molding applications. Edwards *et al.* used a modified SU-8 mold directly as an insert. Aluminum and titanium were sputtered on the SU-8 to reinforce structural integrity of the structures and facilitate better release of the polymer (b0205 Edwards *et al.* 2000). Madou *et al.* combined deep reactive ion etching (DRIE), PDMS, and epoxy to create a mold. DRIE etched the channels, followed by PDMS cast to form the negative pattern of the structures. The epoxy resin was then used to cast the master replica (b0460 Madou *et al.* 2001). b0375 Kim *et al.* (2002) reported creating micromachined mold inserts by electroplating nickel on PDMS. Svedberg *et al.* used injection molding to produce microelectrospray tips for electrospray ionization for coupling with a time-of-flight mass

spectrometer. Svedberg *et al.* fabricated a mold insert by patterning photoresist on 100-mm silicon wafers and wet etching microchannels into the silicon. Nickel was electroplated to form a mold, which was then placed into a compact disk (CD) injection molding machine using polycarbonate (PC) and PMMA (Svedberg *et al.* 2003). Melin *et al.* used a CD Zeonor injection molding technique that combined e-beam evaporation of silica with a PDMS–Zeonor membrane to create a cell culture device. Zeonor provided quick cycling times and the ability to create multiple devices on an individual CD. The device dramatically increased the volume of devices produced in a given week compared to the same process undertaken with soft lithography (Melin *et al.* 2005). Dang *et al.* (2005) reported a method for mass producing 10-channel CE devices for high-throughput genetic analysis. In an attempt to reduce the costs required for serially producing CE chips in glass, Dang *et al.* explored polymer molding for their CE chip design. The design consisted of 10 square channels (50 μm), with 100 μm separating the channels. The mold was generated using deep X-ray lithography to create a master PMMA chip. The channel walls were inclined (85°) to allow for better release of the molded part. For durability, nickel was electroplated onto the PMMA master to ensure sustainable, defect-free molded parts (Becker and Gartner 2000, Yang *et al.* 2001, Dang *et al.* 2005, McCormick *et al.* 1997, Ouellette 2003). The continued development of novel rapid prototyping techniques for mold inserts will greatly enhance the influence injection molding has on microsystem fabrication.

1.12.5.2 Casting

The use of casting for rapid prototyping overlaps with other mold-based microfabrication techniques. Casting encompasses the various types of mold patterning processes such as standard lithography, etching, or laser ablation to create a master pattern to form a replica part in polymers, ceramics, and metals. For most microsystem applications low-cost biocompatible polymers like PDMS are used to produce the replica parts (see Section 1.12.4.1). The mold patterning technique selected will ultimately determine the cost, time, durability, and resolution of the formed parts.

1.12.5.2.1 Applications

The use of casting has been an important rapid prototyping tool for microfluidics researchers. The Whitesides and Quake Research groups highlighted the advantages of casting PDMS for microfluidic systems. Duffey *et al.* demonstrated the implementation of a CE microfluidic configuration in an oxidized PDMS chip (Duffy *et al.* 1998). Anderson *et al.* showed the possibility of creating complex 3D microfluidic networks using casting techniques. Interweaving channels and serpentine channels were cast using multilayer lithography steps (Anderson *et al.* 2000). Unger *et al.* illustrated the capabilities of multilayer PDMS devices that could be used for the active movement and control of fluids through pneumatic actuation of a thin membrane. Microvalves and peristaltic micropumps have been characterized and reported (Studer *et al.* 2004, Unger *et al.* 2000). Since these initial demonstrations of casting for microfluidics, complex microfluidic devices for biological assays and protein deposition have also been reported. McDonald *et al.* (2001), by utilizing PDMS casting, created a disposable microfluidic network for an enzyme-linked immunosorbent assay (ELISA) detection assay. Bernard *et al.* utilized reactive ion etching to etch channels in a silicon wafer for casting microfluidic biomolecule deposition tools in PDMS. The PDMS deposition tool confined solutions of interest to channels that would pattern a substrate with biomolecules. A second deposition tool will replace the first perpendicular to the original flow lanes, creating intersecting regions where binding events can take place (Bernard *et al.* 2001). Xurography (see Section 1.12.3.5) has also been used to form a casting master for direct molding with PDMS (Bartholomeusz *et al.* 2005). The development of novel, low-cost mold patterning techniques will continue to make casting an integral part of rapid prototyping in research development applications.

1.12.5.3 Hot Embossing

Hot embossing, like injection molding, uses polymers as the primary structural material. Using polymers in conjunction with a simple fabrication process allows hot embossing to be one of the ideal methods for fast, inexpensive replication of microsystems. Additionally, this process is good for creating high aspect ratios and small structures. The feature size and quality depend mainly on the master mold and its fabrication process. Depending on the application, master mold fabrication methods can range from classic photolithography to LIGA (LIGA is a German acronym for X-ray lithography (X-ray lithographie), electroplating (Galvanoformung)). Some limitations of hot embossing are a restriction to planar

features, difficulty in creating multidepth features, and a requirement that all polymers used have a glass transition temperature (T_g). Overall, with the wide range of polymers and master mold fabrication methods, hot embossing has the potential to fit the requirements of a large variety of applications.

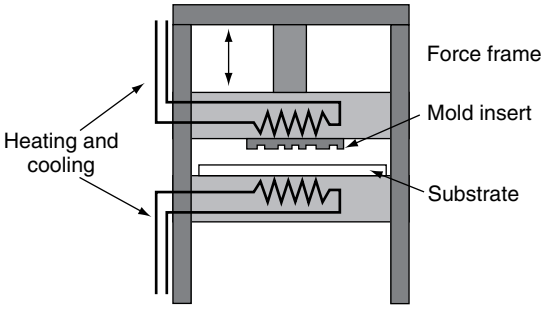
s0295 ***1.12.5.3.1 Fabrication process***

p0635 The first step in hot embossing is to choose a polymer that is compatible with both hot embossing and the application desired. Some common polymers used in hot embossing are PC, PMMA, polyetheretherketone (PEEK), and polystyrene (Becker and Heim 2000, Truckenmuller *et al.* 2002). PC, PMMA, and polystyrene are all transparent, which allows the use of these polymers in optical applications (Fleger *et al.* 2004). Other polymers, like PEEK, may be tougher and useful for applications with higher stresses.

p0640 The second step in developing a hot embossing process is choosing which fabrication method to use to create the master mold, which is a relief structure of the design. Photolithography is the classic method for mold fabrication with hot embossing. Photoresist on a silicon substrate can be electroplated with a metal, like nickel, to create metal master molds (Becker and Heim 2000, Fleger *et al.* 2004). Unfortunately, this method has limitations with regard to aspect ratio. An alternative method is DRIE, which can allow for high aspect ratios and vertical walls (Becker and Heim 2000). Here, a silicon substrate can be used as the embossing tool because the silicon can be directly etched instead of a resist layer. This method, though, can yield high surface roughness and is relatively expensive (Narasimham and Papautsky 2004). Another expensive method that also yields vertical walls and high aspect ratios but has very low surface roughness is LIGA (Becker and Heim 2000). Mechanical machining like computer numerical controlled machining has been used to machine steel or nickel molds. These types of masters have very long lifetimes, but are only good for relatively large featured designs (Narasimham and Papautsky 2004), though the ability of these tools is improving (Hupert *et al.* 2006).

p0645 The material used to develop the master mold is critical to determining the success of the hot embossing operation. The material generally needs to be stable at the glass transition temperature of the polymer and should be strong to withstand multiple uses; also, it should be thermally conductive and smooth on all mating surfaces. The surface roughness usually depends on what type of fabrication method is used to make the mold. Nickel masters are usually silicon substrates with nickel electroplated onto them. Electroplating, unfortunately, is associated with problems such as nonuniformity, bubbles, poor adhesion to the substrate, and difficulty in plating high aspect ratio structures (Narasimham and Papautsky 2004). Silicon is also used, but as mentioned before, the techniques used to etch silicon can lead to high surface roughness. A unique material used by Narasimhan and Papautsky (2004) is PDMS. Intuitively, PDMS would not be ideal material for hot embossing because of its soft malleable nature, but through parameter optimization quality devices were fabricated and the PDMS mold withstood multiple uses. Thus, master mold material is not restricted to typical stiff and hard materials.

p0650 To begin replication, the master mold is placed within a hot embossing press as seen in **Figure 17** (Becker and Heim 2000), which consists of two hot plates and a force mechanism. The master is placed on one hot plate and the polymer substrate is placed on the other. The two plates are heated independently while pulling a vacuum on the entire chamber. Once the hot plates have reached the desired temperature, a certain temperature above T_g, the two plates are pressed together for a specific force and time. After the allotted time, the plates are cooled while keeping the force constant. After cooling, the de-embossing step pulls the two plates apart (Heckele 2003, Simdikova *et al.* 2002). Another type of process is the continuous process in which the master mold is replicated on a heated belt. A polymer sheet is pushed through the heated belt and a base, thereby replicating the mold multiple times on a single sheet (Madou 2002).



f0085 **Figure 17** Basic setup for a hot embossing press (Source: Becker H, Heim U 2000 Hot embossing as a method for the fabrication of polymer high aspect ratio structures. *Sens. Actuators* 83, 130–5. © 2000, reproduced with permission from Elsevier.)

s0300 ***1.12.5.3.2 Process problems and limitations***

p0655 Although the hot embossing process seems simple, there are many parameters that must be considered. Depending on the dimensions of the design, time, temperature, and pressure must be optimized to ensure full filling of the master mold channels. With small channel dimensions, the flow of the polymer into these spaces can be difficult. This concept is the same for deep or high aspect ratio structures. Optimization of the parameters was studied by Shen[b0605] *et al.* (2002). When the temperature is raised, the height of the polymer reaches into channels increases. Although an increase in temperature leads to an increase in polymer flow, too large an increase will cause the polymer to no longer hold the shape of the mold. Also, the polymer and master materials have different thermal expansion coefficients, and if the operation temperature range is too large high stresses will be placed on the polymer material. An increase in pressure has the same effect as temperature, but increasing pressure can cause high stresses that may break the polymer substrate. By increasing the molding time, the polymer height can also be extended. The height, though, was found to increase to a maximum point and lengthening the time after this point has no effect.

p0660 A second challenge is the de-embossing step. With high temperatures and pressures a certain amount of adhesion occurs between the master and the polymer substrate; therefore, during de-embossing, when the two plates are pulled apart, damage can occur to the fabricated structures. To alleviate distortion, releasing agents or antiadhesive films may be used by coating the mold with a thin layer before pressing it into the polymer (Becker and Heim[b0055] 2000, Madou[b0455] 2002). Unfortunately, if hot embossing is used for a life science application, releasing agents are not preferred because they can contaminate the surfaces and reduce biocompatibility. A second method to reduce de-embossing damage is reducing surface roughness because high surface roughness can cause large amounts of friction. For structures having high aspect ratios above 0.5 to achieve good de-embossing, surface roughness must be less than 80-nm rms. Fortunately, some fabrication processes like LIGA can achieve surface roughness of 10-nm rms and ASE-processed silicon can achieve 8-nm rms (Becker and Heim[b0055] 2000). A final method to alleviate high stresses is to create wall angles that are less than 90° (Becker and Heim[b0055] 2000). By doing so, vertical forces are reduced. Some other problems that may occur in hot embossing are high stresses due to pressure on the substrate and bonding problems during packaging.

p0665 General limitations of hot embossing are largely based on the limitations of the mold fabrication process. For example, if typical wet silicon etching is used as the master mold fabrication, the shape of the channels within the polymer substrate will not be rectangular. The overall maximum aspect ratio is around 50 and the minimum feature size is in the nanometer range, which leads us to nanoimprint lithography. Hot embossing tooling can be relatively expensive, which is why it is preferable for low and midrange production. A hot embossing press can cost around US$150 000. Another cost consideration is choosing a polymer because they have a wide range of prices depending on the type of material. PC, for example, can cost about US$24 for a 12″ × 12½″ sheet. In contrast, a same-size sheet of PEEK will cost about US$600 (www.usplastics.com).

s0305 ***1.12.5.3.3 Advantages and disadvantages of hot embossing***

p0670 Hot embossing has many advantages and disadvantages compared to other microfabrication methods. Hot embossing is good for small structures and high aspect ratios (Becker and Heim[b0055] 2000). Another advantage is the simple fabrication process used in hot embossing, which is because of the small number of steps required for fabrication (Heckele[b0295] 2003, Simdikova[b0615] *et al.* 2002, Truckenmuller[b0680] *et al.* 2002). After the master mold is created, fabrication of the fluidic channels can be done in minutes and repeated several times. The simplicity of fabrication inherently leads to another advantage, a strong potential for mass production. Mass replication also provides a possibility to design disposable parts (Truckenmuller[b0680] *et al.* 2002). Other fabrication methods that are timely make disposability a costly function. The inexpensive cost of the polymers also makes it possible to manufacture disposable parts; low long-term costs is another advantage. Finally, many polymers are also biocompatible and are currently used in many medical applications.

p0675 Hot embossing also has many disadvantages. Because the channels are created by pressing a mold into a planar sheet, the features that can be created must also be planar. This is a huge disadvantage compared to traditional methods like UV lithography, where multiple layers can be manufactured easily. Hot embossing's cousin, injection molding, which also can be inexpensive and quick, can also create nonplanar features. Another disadvantage is the high residual stresses (Becker and Heim[b0055] 2000). The use of temperature in conjunction with pressure on polymers, which are not the most durable materials, can

cause cracks and broken edges unlike in silicon wet etching. Corresponding to high residual stresses, multiple-depth features are difficult to make because of the required higher temperatures and pressures (Madou 2002[b0455]). Hot embossing also has high initial costs. For example, if the master mold is made using LIGA, the cost of paying for a LIGA mold will be extremely expensive, along with having to buy the LIGA mold materials and a hot embossing press.

1.12.5.3.4 Hot embossing applications

Hot embossing is a relatively new method for microfabrication. Currently, the most common explorations are in the fields of optics, motors, bioMEMS, and IC packaging industry. In the IC industry this method is being explored as a packaging solution called molded interconnect devices (MIDs) (Kunststoffe 1998). The concept of these MIDs is to integrate an electronic circuit in a polymer housing. Through this packaging system the electronic parts can be arranged three-dimensionally and they can consequently reduce the materials needed and the total volume.

A common and simple use of hot embossing in optics is fabrication of waveguides. Fleger *et al.* (2004[b0215]) accomplished this task by using a nickel master mold made using UV lithography with nickel electroplating and embossing into a PMMA substrate. The polymer waveguides were characterized by performing propagation loss and transmission measurements. Flegler also demonstrated the simultaneous manufacturing of microfluidics and optics on a chip using hot embossing.

Another unique example of using hot embossing is electrostatic comb drives. Zhao and Cui (2003[b0795]) successfully designed a comb drive out of PMMA. In this case, the master mold was fabricated out of silicon using DRIE. Multiple embossing layers as well as metallization steps were employed, showing the flexibility and compatibility of the hot embossing process. The pull-in voltage, stroke length, and natural frequency were all reasonable and the process could easily compete with traditional silicon methods.

A final application example of hot embossing is a microfluidic analysis chip, which is the traditional use of hot embossing. A good example is from Truckenmuller *et al.* (2002[b0680]). To create their mold, micromachined trenches were milled in brass plates. Next, the mold was placed into a hot embossing press with a two-layered substrate of polystyrene consisting of a thin top layer of high-impact polystyrene and a thick bottom layer of polystyrene. The substrate was coated with a heat-sealing layer and then typically pressed together with the mold in the embossing press. By placing an electrode in between the two layers of the polystyrene, Truckenmiller was able to create a fluidic device for CE.

Various other applications of hot embossing have been explored, with the majority of them being related to microfluidics. Overall, hot embossing can be a low-cost method for low-range to midrange fabrication of molded polymer microdevices.

1.12.5.4 Roller Embossing

The process of roller embossing is a rapid fabrication technique generally using a roller covered with a thin mold that patterns a polymer or some other moldable material. The embossed material is typically formed through a heat-forming or photocuring configuration. Roller embossing is a useful tool for creating large arrays of continuous microstructures. Chang *et al.* reported the use of roller embossing of a UV-curable photopolymer in a custom UV exposure facility to form polymer microlens arrays. Before fabrication, a flat mold is generated from electroplating nickel or some other durable metal onto a polymer microlens master substrate. The resulting flat mold consisting of microlens indentations is wrapped around a cylindrical device to form the roller. The UV-curable polymer is embossed onto a glass substrate as the roller presses the microlens arrays. The roller embossing is implemented within the UV exposure zone, allowing the polymerization and formation of the microstructures (Chang *et al.* 2006[b0100]). Gallagher demonstrated roller embossing for fuel cell applications using curable polymer materials. The technique is used to form fluid flow cells on separator plates that sandwich the membrane electrolyte assembly (MEA). The flow cells are used to circulate coolant or supply reactants to the MEA (Gallagher 2004[b0240]). A similar method has been used to fabricate antireflective microstructures for LCD displays (Parrika and Saarinen 2005[b0550]).

1.12.6 Conclusions

Though MEMS and microfabrication have been dominated by processes that require expensive tooling, a large number of techniques have been developed that can help eliminate the high costs associated with traditional MEMS processes. One of the easiest ways to reduce costs is to use tools available in the mass consumer market, such as laser or

ink-jet printers for making masks. Techniques such as xurography can use commercially available double-sided tapes that can not only produce high-resolution devices, but also eliminate most of the processing steps such as lithography, etching, and bonding. The recent use of plastics has also been a major development that has the capability to drive down costs. Directly patterning plastics using photosensitive polymers may be the simplest, but laser cutting and molding of polymers is becoming increasingly commonplace. The adoption of rugged soft polymers for microfluidics research (soft lithography) has rapidly driven the field forward, since nearly any researcher can easily set up the facilities needed for prototyping. The precision with which plastics can be molded has led to interesting applications of techniques such as soft lithography, which allows nanoscale features to be generated repeatably and reliably. Thus, for some applications, the inexpensive techniques are replacing the more traditional MEMS techniques as the primary processing method as the function of plastics is more amenable to biomedical and microfluidic applications.

p0715 In many cases, the question is no longer, "Can an inexpensive microfabrication technique do the job?" but "Which inexpensive process is best for this application?" The answer to this question is not always simple, but a few guidelines can make the decision process simpler. For example, some of the techniques discussed in this chapter are limited in their ultimate resolution, such as screen printing, xurography, and laser printing, but for larger microscale devices they are the simplest and least expensive. Combining some inexpensive methods with some more expensive tools can lead to high precision at a relatively low cost. For example, using e-beam lithography to make a soft lithography mold can lead to inexpensive nanoscale structures, even if the e-beam step is rather expensive. Some of the techniques are better for prototyping than for mass production, such as soft lithography and xurography, but new efforts to commercialize these techniques may nullify this current limitation. The pure molding processes are typically more expensive unless high volumes of devices are fabricated, so they are typically precluded from prototyping. The one limitation of most of these techniques is that they do not necessarily work well with silicon, the traditional MEMS material. Thus, converting to a less expensive process often requires a change of material, but if circuits are not the focus, this conversion can often be painless, not to mention less expensive.

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Biographies

Bruce K. Gale, currently Director of the Utah State Center of Excellence for Biomedical Microfluidics and an Assistant Professor of Mechanical Engineering at the University of Utah since 2001, has been working in the area of microfluidics and micro-total-analysis systems (μ-TAS) for the past decade. His interests include lab-on-a chip devices that require a variety of microfluidic components for the completion of complex and challenging medical and biological assays. These components fall into three broad categories: sample preparation, sample separation or analysis, and detection. His work has recently involved micromachined particle separation systems and detectors, microarray manufacturing methods, and sensors related to these applications. Specifically, he is working to develop a microfluidic toolbox for the rapid design, simulation, and fabrication of devices with medical and biological applications. The ultimate goal is to develop platforms for personalized medicine, which should allow medical treatments to be customized to the needs of individual patients.

Mark A. Eddings is a Doctorate student in Bioengineering at the University of Utah. He also received his undergraduate degree in Mechanical Engineering from the University of Utah in 2004. While working on his undergraduate degree, he worked as an Engineering Intern for Medron, a medical device manufacturing company, specializing in percutaneous catheters and other related devices. He has been an NSF IGERT fellow and is currently working in the Utah State Center of Excellence for Biomedical Microfluidics as a research assistant. His research interests focus on clinical applications of microfluidic immunoassays for therapeutic monitoring and point-of-care diagnosis. His previous research consisted of micropump development for lab-on-a-chip applications.

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