
Microfabrication, Microstructures and Microsystems

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This review gives a brief introduction to materials and techniques used for microfabrication. Rigid materials have typically been used to fabricate microstructures and systems. Elastomeric materials are becoming attractive, and may have advantages for certain types of applications. Photolithography is the most commonly used technique for the fabrication of structures for microelectronic circuits, microelectromechanical systems, microanalytical devices and micro-optics. Soft lithography represents a set of non-photolithographic techniques: it forms micropatterns of self-assembled monolayers (SAMs) by contact printing and generates microstructures of polymers by contact molding. The aim of this paper is to illustrate how non-traditional materials and methods for fabrication can yield simple, cost-effective routes to microsystems, and now they can expand the capabilities of these systems.

Keywords: Microfabrication, microsystems, microlithographic techniques.

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1

Introduction

Microfabrication is increasingly central to modern science and technology. Many opportunities in technology derive from the ability to fabricate new types of microstructures or to reconstitute existing structures in down-sized versions. The most obvious examples are in microelectronics. Microstructures should also provide the opportunity to study basic scientific phenomena that occur at small dimensions: one example is quantum confinement observed in nanostructures [1]. Although microfabrication has its basis in microelectronics and most research in microfabrication has been focused on microelectronic devices [2], applications in other areas are rapidly emerging. These include systems for microanalysis [3–6], micro-volume reactors [7, 8], combinatorial synthesis [9], microelectromechanical systems (MEMS) [10, 11], and optical components [12–14].

One particularly exciting use for microanalytical devices is in the separation and analysis of chemical and biological substances [3–6]. These devices require only small quantities of reagents, have relatively short analysis times and can show efficiencies in separations that are better than larger counterparts. In the past few years, a number of miniaturized total chemical analysis systems (μ TAS) [15] have been developed that perform all sample-handling steps in an integrated fashion. For example, capillary electrophoresis (CE) devices using microchannels etched into planar glass substrates have attracted attention [16–18] for their use in applied molecular genetics. Systems for free-flow electrophoresis [19], gas chromatography [20], liquid chromatography [21, 22], capillary electrophoresis [23] and micellar electrokinetic capillary chromatography (MECC) [24] have been developed. Rapid and efficient capillary zone electrophoretic separations in micromachined channels (open, gel-filled or polyacrylamide-coated) on quartz substrates have also been demonstrated [3, 25, 26].

Devices for performing not only analysis, but also chemical synthesis in miniaturized systems (or microreactors) are also being developed [7, 27–34]. An array of chemical tools on a chip would make it possible, for example, to synthesize, analyze and characterize extremely small amounts of product ($\sim 10^{-12}$ l) [6]; these systems will be useful for combinatorial synthesis as part of new procedures for the parallel synthesis and screening of large numbers of compounds. Development of several prototypical microreactors suggest that microfabrication will play an important role in biology and chemistry: examples include DNA chips for high-speed DNA sequencing [35–38]; microchips for carrying out the polymerase chain reaction (PCR) [39]; microchip-based apparatus for the synthesis and characterization of libraries of peptides and oligonucleotides [40]; and microchip-based drug discovery using electronic addressing for the investigation of small objects such as single biological cells [41].

In addition to their biological and chemical applications, microstructures used in MEMS have evolved rapidly to integrate electronics with monitoring, actuating, and controlling tools (including chemical, optical, and mechanical sensors) for use in engineering. In the past few years, the scope of fabrication

techniques and the types of devices categorized as MEMS have widened dramatically [10, 11, 42, 43]. Most are fabricated from silicon using standard microlithographic techniques (silicon bulk micromachining and polysilicon surface micromachining) [44–46]. With these methods, thousands of mechanical elements (for example, cantilevered beams, springs, linkages, mass elements and joints) can be batch-fabricated on a single silicon substrate [9, 11]. Micro-actuators, micromotors and microengines [46] have been fabricated for optical switches, fluid pumps [47], systems for drug delivery and microchemical analysis and high-speed rotational gyros for navigation [48–51]. More recently, surface micromachining techniques have been used to fabricate miniaturized optical components [12–14]. A free-space micro-optical system comprising three-dimensional microgratings, micromirrors and microlenses is one example [14, 52]. These and similar miniaturized optical devices are attractive for applications in spectrometers, free-space optical interconnects, display devices, sensors, optoelectronic packages and data storage devices.

These current and potential applications motivate the development of techniques for fabricating and manipulating objects with nanometer and micrometer feature sizes. This review gives a brief introduction to materials and techniques commonly used for microfabrication; its focus is on those currently being explored in our laboratory. Our aim is to illustrate how non-traditional materials and methods for fabrication can yield simple, cost effective routes to microsystems, and how they can expand the capabilities of these systems. In a concluding section we provide brief descriptions of a number of other techniques for fabrication that, like those we are developing, may provide variable alternatives to photolithography.

2

Requirements on Materials for Microsystems

Miniaturized systems for performing chemical/biochemical reactions and analysis require cavities, channels, pumps, valves, storage containers, couplers, electrodes, windows and bridges [53]. The typical dimensions of these components are in the range of a few micrometers to several millimeters in length or width, and between 100 nm and 100 μm in depth and height. An extensive set of techniques for fabricating these microstructures is discussed in Sect. 3.

2.1

Rigid Materials for Microsystems

Microsystems can be built on various substrates with a range of materials: crystalline silicon, amorphous silicon, glass, quartz, metals, and organic polymers. Single-crystal silicon substrates have been used in most areas of microfabrication for a range of excellent reasons:

1. Silicon processing itself can be carried out using thin films of organic photoresists as resists against etching, and this technology is very highly developed.

2. Two- and three-dimensional shapes and patterns can be reproduced in silicon with high precision using bulk and surface micromachining techniques [46, 54]
3. Silicon devices can be batch-fabricated using the technology currently used for fabricating integrated circuits.
4. Silicon/silicon dioxide is stable chemically and thermally.

Crystalline silicon also has several disadvantages: it is expensive, brittle, and opaque in the UV/visible regions, and its surface chemistry is complicated to manipulate. As alternatives to silicon, glass, quartz and some rigid organic polymers (for example, epoxy, polyurethane, polyimide, polystyrene and polymethylmethacrylate) have properties that make them useful as materials for microsystems [55, 56]. In particular, they are transparent in the visible and UV regions and so can be easily adapted to optical detection in microanalytical devices. Microstructures of these materials can be replicated readily using low-cost methods such as replica molding and embossing [55–61]. In addition, the surface properties of these substrates (e.g. wetness ability, adhesion, surface adsorption and surface reactivity) can be modified rationally using a variety of surface chemistries. Techniques involving the formation of self-assembled monolayers (SAMs) [62] and the attachment of complex macromolecules [63] (e.g. immunoglobulins and nucleic acids) provide new routes to tailoring surface properties. Polymers are, however, not stable at high temperatures and their low thermal conductivities may limit their use in applications requiring high local power dissipation (e.g. in CE).

Integration of various components of a miniaturized device requires methods for bonding materials to substrates [64]. The most commonly used technologies for joining glass and silicon components include:

1. Anodic bonding [65], which uses electrostatic attraction to bring a glass wafer into contact with a silicon wafer and to form covalent bonds between them;
2. Silicon fusion bonding [65], which employs a similar mechanism to bond together the surfaces of two slightly-oxidized silicon wafers at high temperatures; and
3. Thermal bonding [66], which joins two glass wafers by locally melting them under controlled conditions.

Bonding technologies for organic polymers will probably be based on adhesives and other ones that are still being developed.

2.2

Elastomeric Materials for Microsystems

Rigid materials have typically been used to fabricate MEMS and optical components (for example, diffraction gratings, lenses and mirrors). These materials have the advantages of structural rigidity and strength. In certain applications, however, rigid materials may not provide the only solution to structural problem: adaptive optics is such an application [67]. Adaptive optics have com-

monly been constructed by assembling smaller, rigid elements that can be moved independently to modify characteristics [68]. Elastomers are well suited as materials for similar systems. We have created a new route for fabricating optical elements and optical systems from elastomeric materials such as poly(dimethylsiloxane), PDMS [69]. These types of optical components and devices have characteristics that can be controlled by changing their shapes with mechanical compression or extension. There are several advantages to using PDMS as a material for adjustable optical elements:

1. It can be deformed reversibly and repeatedly without permanent distortion or relaxation of features [70].
2. It can be molded at a scale suitable for optical applications (with feature sizes in the range of 0.1 – 10 μm) with high fidelity [71].
3. It is optically transparent down to ~ 300 nm [72].
4. It is durable and chemically inert.
5. It is non-toxic, commercially available and inexpensive.

We have demonstrated the concept of elastomeric optics by fabricating elastomeric lenses, corner cubes, mirrors and diffraction gratings [69]. We have used these components as photothermal detectors [73]; devices for measuring displacement, strain, stress, force, torque, and acceleration [70]; optical modulators and display devices [74]. In these devices, the active optical element is a block of PDMS with the relief of a binary diffraction grating on its surface. Mechanical compression/extension controls the relative optical path of light passing through the grating; this change in path causes the patterns of diffraction to be coupled to the compression/extension. Fabrication of elastomeric light valves represents additional examples of elastomeric optical devices [75]. One such example is an array of retroreflective corner cubes [76]. The amount of light transmitted through the valve is controlled by mechanical compression and extension against the surfaces of the PDMS blocks in the out-of-plane direction. These deformable elastomeric light valves may have applications in display devices, energy saving windows, sensors (accelerometers and pressure gauges) and photolithographic systems (such as photomasks) [77].

3

Microlithographic Techniques

In the following sections, we begin with a description of photolithography, then focus on a number of methods developed in our laboratory and conclude with some other non-traditional techniques. More extensive descriptions of traditional approaches are reviewed elsewhere [78].

3.1

Photolithography

Photolithography is the most commonly used microlithographic technique [2, 78]. In photolithography, a substrate, spin-coated with a thin layer of photo-

sensitive polymer (photoresist), is exposed to a UV light source through a photomask. The photomask is typically a quartz plate covered with patterned microstructures of an opaque material (usually chromium). The photoresist exposed to UV light becomes either more (positive resist) or less (negative resist) soluble in a developing solution. In either case, the pattern on the photomask is transferred into the film of photoresist; the patterned photoresist can subsequently be used as the mask in doping or etching the substrate.

In addition to conventional photoresist polymers, Langmuir-Blodgett (LB) films and SAMs [79–81] have been used as resists in photolithography. In such applications, photochemical oxidation, cross-linking, or generation of reactive groups are used to transfer micropatterns from the photomask into the monolayers [82–84].

Photolithography is widely used to fabricate structures for microelectronic circuits, MEMS, microanalytical devices and micro-optics. It has, however, a number of disadvantages. It is a relatively high-cost technology and the investment required to build and maintain photolithographic facilities makes this technique less than accessible to many chemists and biochemists. It can not be applied easily to curved surfaces (the formation of micropatterns and microstructures on non-planar substrates is important in the fabrication of certain types of optical and MEMS devices). It is applicable to only a small set of materials and it gives little control over the properties of the surfaces that are generated. These limitations have motivated the development of alternative, low-cost microlithographic techniques for manufacturing microstructures.

3.2

Soft Lithography

We have developed a set of non-photolithographic techniques for microfabrication that are based on the printing of SAMs and molding of organic polymers; we refer to these techniques, collectively, as soft lithography. Soft lithographic techniques include microcontact printing [80], micromolding in capillaries [85], microtransfer molding [86] and replica molding [60, 71]. Embossing [58], injection molding, and some techniques based on electrochemical deposition and etching might also be included as soft lithographic techniques. The capability and feasibility of soft lithography have been demonstrated by the fabrication of microstructures and systems in polymers and metals on a variety of substrates.

3.2.1

Microcontact Printing

Microcontact printing (μ CP) is a technique that uses an elastomeric stamp with relief on its surface to generate patterned SAMs on the surface of both planar and curved substrates [87, 88]. SAMs are highly ordered molecular assemblies that form spontaneously by chemisorption of functionalized long-chain molecules on the surfaces of appropriate substrates [79, 89]. Well-established systems of SAMs include alkanethiolates on coinage metals (Au, Ag, Cu) [90]; alkylsiloxanes on hydroxyl-terminated surfaces (Si/SiO₂, glass) [91]; carboxylic and

hydroxamic acids on oxide of metals [79, 92]; alkylphosphonates on ZrO_2 [93, 94]; and alkylphosphonic acids on Indium Tin Oxide [95]. The thickness of a SAM is about 2–3 nm, and can be varied with an precision of ~ 0.1 nm by changing the number of methylene groups in the alkane chain. The surface properties of a SAM can be controlled by modifying the tail groups (that is, the functional groups distal to the surface). SAMs have many of the features that are attractive in microfabrication:

1. They are quasi-equilibrium structures that are at, or close to, thermodynamic minima, and that tend, as a consequence, to be self-healing and defect-rejecting [62].
2. SAMs function as ultrathin resists against certain types of etches, and patterned SAMs can also be used as templates to control the nucleation and deposition of other materials (e.g. polymers [96], copper [97] and mammalian cells [98]).
3. They can be handled outside of clean room facilities, and certain types of fabrication involving SAMs are relatively low in cost compared with conventional photolithographic methods.

Figure 1 outlines the procedure used for μCP . This technique is experimentally simple and inherently parallel. The elastomeric stamp is fabricated by casting a prepolymer of PDMS against a master, which can be prepared using photolithography or other related techniques (for example, micromachining or e-beam writing). We have cast more than 50 stamps against a single master. To print hexadecanethiol (HDT) on gold, the “ink” used is a solution of HDT in ethanol (~ 2 mM). After the PDMS stamp is inked, it is brought into contact with a substrate to form patterned SAMs (Fig. 1A). Large area patterning (10 – 100 cm^2) is possible either by using a large flat stamp or by mounting a thin PDMS stamp onto a cylindrical rod and then rolling the stamp across the substrate (Fig. 1B) [99]. μCP also allows generation of micropatterns and microstructures on curved substrates by rolling curved substrates across an inked stamp (Fig. 1C) [87]. Conventional lithography lacks the depth of focus to pattern on curved substrates. We have been able to generate patterned SAMs of alkanethiolates on coinage metals [90, 100–102], patterned SAMs of alkylsiloxanes on hydroxyl-terminated surfaces [103–105]. CP has also been extended for patterning arrays of colloidal particles of Pd on Si/SiO₂ [106]. In μCP , each PDMS stamp can be used more than 100 times without degradation in performance; much higher levels of use may also be possible but have not been explored.

μCP followed by selective wet etching allows the formation of arrays of microstructures of coinage metals with controlled shapes and dimensions [96, 107]. This capability has direct applications in the fabrication of sensors [108], arrays of microelectrodes [109], and diffraction gratings [110]. Moreover, the patterned metallic microstructures can be used as secondary masks in the etching of underlying substrates (for example, Si, SiO₂ and gallium arsenide) to fabricate microchannels and microcavities for microreactors and microanalytical systems [54]. Figure 2 shows several typical examples of microstructures fabricated using the combination of μCP and selective etching. Figure 2A shows

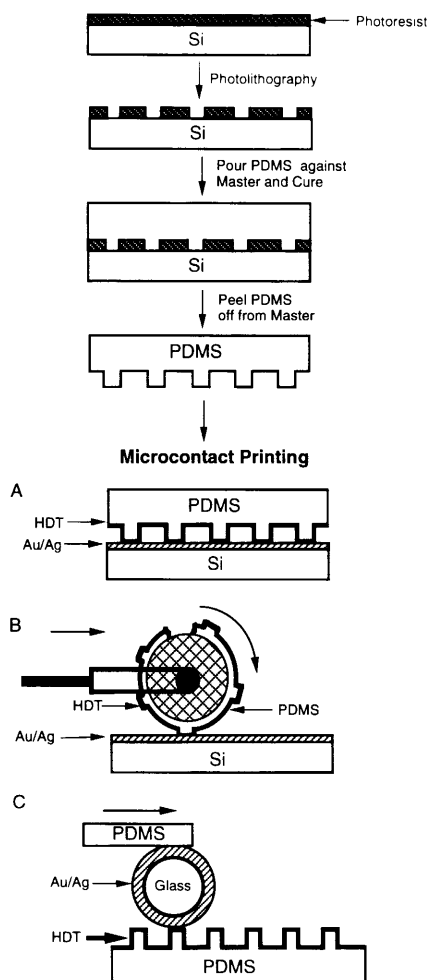


Fig. 1. Schematic procedures for μ CP: (A) printing on a planar substrate with a planar PDMS stamp; (B) printing on a planar substrate with a rolling stamp; and (C) printing on a curved substrate with a planar stamp

a scanning electron micrograph (SEM) of patterned microstructures of Ag on a Si/SiO₂ surface that were generated by μ CP hexadecanethiol with a rolling stamp, followed by selective wet etching in an aqueous ferricyanide solution [107]. We can routinely produce sub- μ m ($>0.3 \mu$ m) features over an area of $\sim 50 \text{ cm}^2$ in a single impression in approximately 30 s [99]. We are beginning to define the registration and distortion of the patterns associated with elastomeric stamps [111]. Figure 2B shows an SEM of patterned microstructures of Ag on Si/SiO₂. Figure 2C shows a cross-sectional SEM of microchannels that were generated in a Si(100) wafer using a combination of μ CP, shadow evaporation and silicon micromachining [54]. Figure 2D shows an SEM of a microtrans-

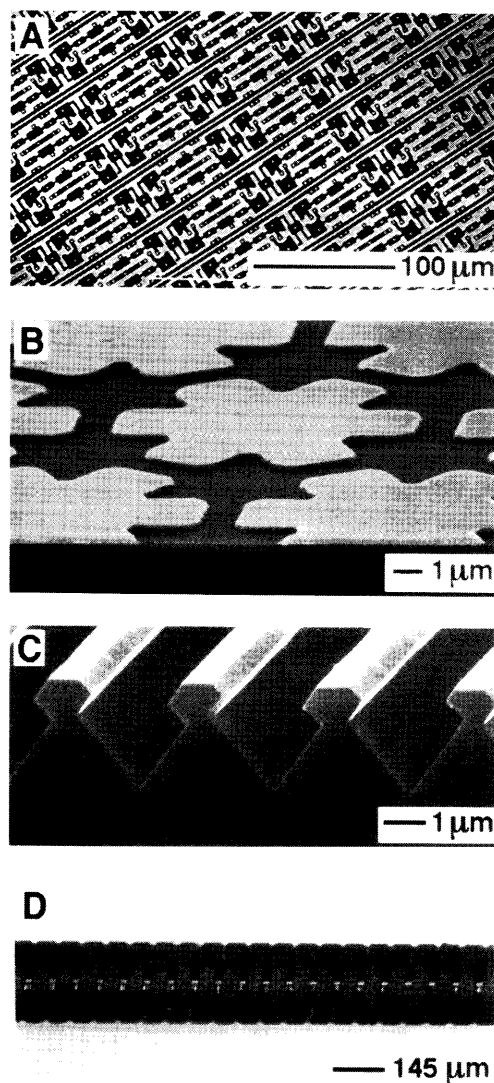


Fig. 2. A, B SEMs of test patterns of silver fabricated using μCP , followed by selective etching; C cross-sectional SEM of microchannels etched in Si(100); and D optical micrograph of a microtransformer fabricated using μCP , selective etching and electroplating

former fabricated using a combination of μCP , selective wet etching and electroplating [112]. Conducting microcoils produced in this way on micro-capillaries have been used for high-resolution proton NMR spectroscopy on nanoliter volumes [113] and as current carriers in micro-inductors [114]. Similar cylindrical structures may be useful as intravascular stents and micro-springs [114].

3.2.2

Molding of Organic Polymers

Formation of replicas by molding against rigid masters has been widely used to manufacture compact disks (CDs) [115] and diffraction gratings [59]. By extending this procedure to include an elastomer as the material for the mold, we have developed a number of techniques for fabricating microstructures of polymers, including micromolding in capillaries (MIMIC) [85, 116, 117], microtransfer molding (μ TM) [86], and replica molding [60, 71]. An elastomeric (PDMS) stamp with relief on its surface is central to each of these procedures (Fig. 3). In MIMIC, a liquid prepolymer (for example, a UV curable polyurethane or a thermally curable epoxy) wicks spontaneously by capillary action into the network of channels formed by conformal contact between an elastomeric mold and a substrate. In μ TM, the recessed regions of an elastomeric mold are filled

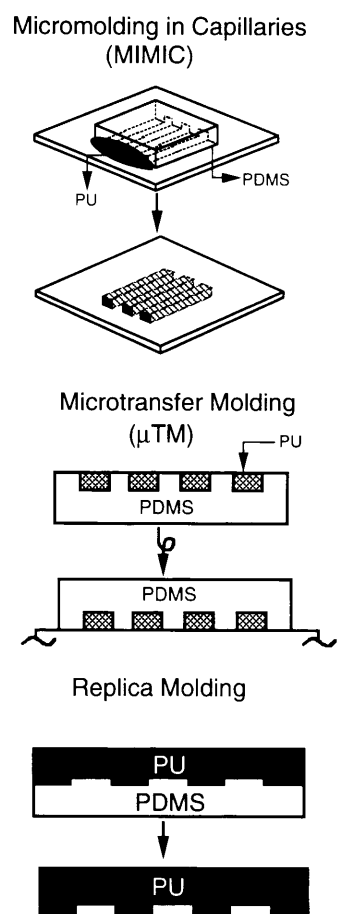


Fig. 3. Schematic procedures for MIMIC, μ TM and replica molding

with a liquid prepolymer, and the filled mold is brought into contact with a substrate. After curing the prepolymer, the mold is removed, leaving a polymer microstructure on the substrate. MIMIC can only be used to fabricate interconnected microstructures. Figure 4A shows an SEM of a free-standing microstructure of polyurethane that was fabricated on an SiO_2 surface using MIMIC, followed by lift-off in an aqueous HF solution [85, 116]. Figure 4B shows polystyrene beads crystallized in microchannels fabricated by MIMIC using an aqueous suspension of the colloidal beads [118]. Arrays of such crystalline microbeads are interesting for potential applications in chromatography and applied optics. μTM can be used to generate both isolated and interconnected microstructures; it can also be used sequentially to fabricate multi-layer structures. The smallest features we have produced using these procedures are parallel lines with cross sections of $\sim 0.1 \times 2 \text{ m}^2$. These dimensions are limited by the PDMS molds used in our work. Figs 4C and 4D show SEMs of two- and three-layer microstructures fabricated using TM [86]. Figs 4E and 4F show SEMs of carbonized polymeric structures (an interdigitated capacitor and an optical deflector) fabricated by μTM [119].

In replica molding, microstructures are directly formed by casting and curing a UV curable polymer against an elastomeric mold. This method is effective for replicating feature sizes ranging from several centimeters to $\sim 30 \text{ nm}$. Figure 4G shows an SEM of a hemispherical object with 100 m corner-cubes on its surface that was fabricated using replica molding against a deformed PDMS mold [60]. Replica molding also provides a convenient route to microstructures with high aspect ratios. Figure 4H shows an SEM of one such structure replicated from a master generated in a thin film of heat-shrinkable polystyrene [120].

Molding against an elastomeric PDMS master has several advantages. First, the elastomer can form conformal contact with a substrate; it can also be released easily, even from complex and fragile structures. Secondly, PDMS provides a surface with low interfacial free energy ($\sim 21.6 \text{ dyn cm}^{-1}$) and low reactivity. As a result, the polymers being molded do not adhere irreversibly to or react with the surface of PDMS. Thirdly, the deformation of PDMS can be controlled easily by mechanical compression, bending and stretching. Taking advantage of this flexibility, we have been able to fabricate microstructures of polymers with controlled shapes on both planar and non-planar surfaces [60].

Microfabrication based on molding is remarkable for its simplicity, for its economy, and for its fidelity in transferring the patterns from the mold to the polymeric structures that it forms. MIMIC, μTM and replica molding have been used to fabricate microstructures of a wide range of materials, including polymers, inorganic and organic salts, sol-gels, polymer beads and precursor polymers to ceramics and carbon. The feasibility of these molding techniques has been demonstrated by the fabrication of chirped, blazed diffraction gratings [60], polymeric waveguides [121], waveguide interferometers/couplers [122], interdigitated carbon capacitors [118], and suspended carbon microresonators [123]. Without steps for transferring patterns, photolithography can only be used to generate microstructures in the classes of polymers that have been developed as photoresists.

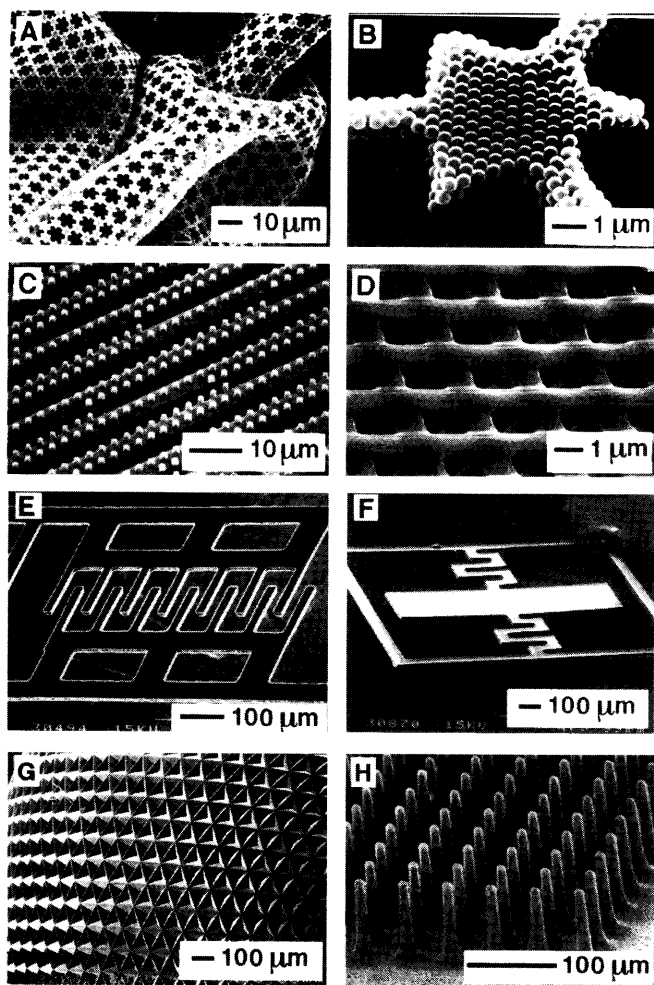


Fig. 4. SEMs of microstructures fabricated using A, B MIMIC; C, D, E, F μ TM and G, H replica molding. See text for details

3.3

Rapid Prototyping

An elastomeric stamp or mold with relief structures on its surface is the key to soft lithographic techniques (see Sect. 3.2). As a result, the utility of these techniques is often limited by the availability of appropriate masters. In general, the masters are fabricated using photolithography. Chrome masks are available commercially from custom fabricators, but the time required for vendors to produce a chrome mask from a design presented in a computer aided design (CAD) file can be weeks, and they are expensive (\sim \\$300 per square inch for features larger than 20 μ m, and \sim \\$500–\\$1000 per square inch for features between 1 and

20 μm). The time and expense involved in generating chrome masks are barriers to the use of photolithography by chemists and biologists and have limited the use of microfabrication in these fields.

Recently, we [124] and others [125] have developed a system that has enabled us to fabricate masters having feature sizes $\geq 20 \mu\text{m}$ rapidly and at low cost. In this technique [124], we draw patterns using computer programs such as Macro-media Freehand or AutoCAD and print them directly onto polymer films using a commercial, laser-assisted image-setting system (for example, Herkules PRO, resolution of 3387 dpi, Linotype-Hell Company, Hauppauge, NY). Using this method, photolithographic masks – transparent polymeric films patterned with microstructures of black ink – can be made in a few hours at a cost of $\sim \$1$ per square inch. Although these masks do not have the durability and dimensional stability required for use in the manufacturing of microelectronic devices, they are suitable for the rapid production of limited numbers of prototype microfluidics, sensors, micro-optics, and microanalytical systems. They also have two other attractive features:

1. They are flexible, and can be used to pattern non-planar substrates.
2. They are thin, and can be stacked on top of one another to generate new types of patterns.

After the patterns on these polymer films are transferred into photoresist films coated on silicon substrates using photolithography, the developed photoresist patterns can serve as a master to make the required PDMS stamps. By combining this method of rapid prototyping with soft lithographic techniques, we can fabricate patterned microstructures of polymers and metals within 24 h of the time that the design is completed. Rapid prototyping makes it possible to produce substantial numbers of simple microstructures rapidly and inexpensively.

The rapid prototyping method has been demonstrated by fabricating structures representative of those used in microanalytical systems. Figure 5 shows two examples: a microCE channel and a surface acoustic wave (SAW) device. Figure 5A shows a schematic design of the pattern used in the microCE. Figs. 5B and 5C show optical micrographs of two areas of the pattern that were etched into a glass slide using the patterned film of photoresist as the mask. Figure 5D illustrates the pattern used for a SAW device and Fig. 5E shows an SEM of a portion of this device (made of silver on Si/SiO₂) that was fabricated by selective etching in an aqueous ferricyanide solution.

At present, the smallest features that can be generated directly using this procedure are $\sim 20 \mu\text{m}$, a size that is limited by the resolution (3387 dpi) of the image-setting system. It should be possible to generate features with smaller sizes by using printers with higher resolution. Even with masks made by the current image-setting system, we are able to generate features significantly smaller than $20 \mu\text{m}$ by using some of the techniques reported previously (e.g. mechanical compression of an elastomeric stamp) [126]. We believe that rapid prototyping paves the way for expanded use of microfabrication (especially when patterns may be complex but require only modest linewidths) in chemistry and biology.

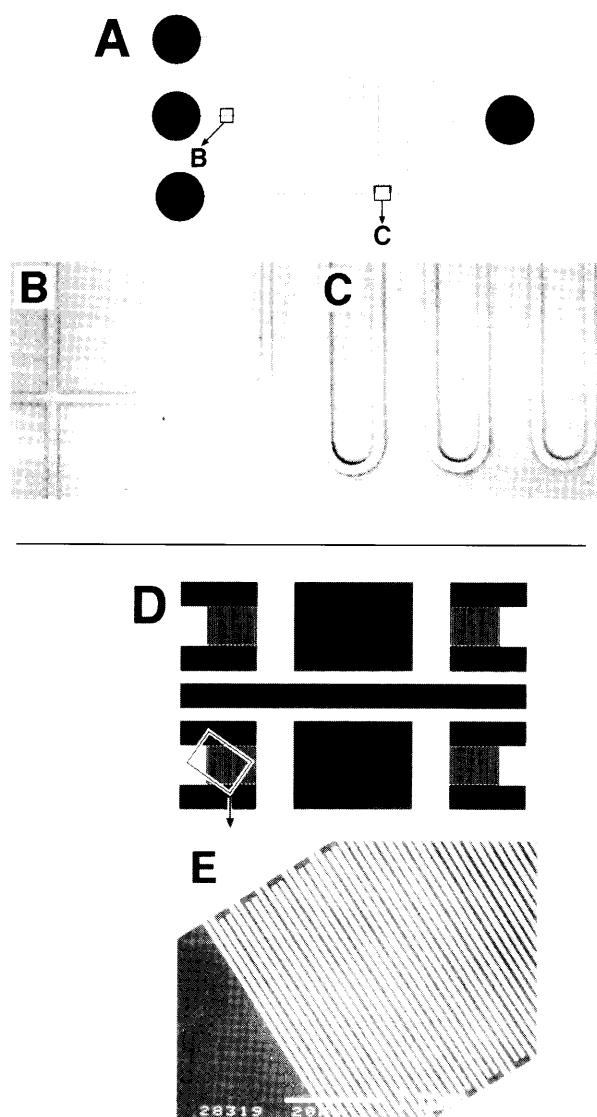


Fig. 5. **A** The designed pattern used in microCE; and **B, C** optical micrographs of two selected areas of the pattern that was transferred into a glass slide. **D** The designed pattern used in SAW device; and **E** an SEM image of a portion of the pattern generated in silver on Si/SiO₂

3.4

Other Methods for Microfabrication

Embossing (or Imprinting) is a low-cost, high-throughput manufacturing technique that imprints microstructures in plastic materials [127]. The manufacture of CDs based on imprinting in polycarbonate is a good example of a large-

volume commercial application of this technique [115]. Until recently, embossing had not been seriously developed as a method for fabricating microstructures of semiconductors, metals and other materials used in semiconductor integrated circuit manufacturing. Work by Chou and coworkers showed that embossing can be used to make features as small as 25 nm and has attracted attention to the potential of this kind of patterning [58, 128]. We have also demonstrated a variant of embossing using an elastomeric master [129]. In this technique, the elastomeric master is wet with an appropriate solvent and is brought into contact with the surface of a polymer. The polymer is softened by the solvent, and the resulting (probably gel-like) polymeric material is molded against the relief structure of the elastomer to form a pattern complementary to that on the surface of the mold.

Injection Molding is an alternative technique used for manufacturing CDs [57]. It has been used to generate microstructures with feature sizes of $>0.5\ \mu\text{m}$. Injection molding combined with sintering technology provides a potential route to complex structures made of nearly every sinterable material or material combination [130]. The capability of this technique has been demonstrated by producing fiber-reinforced metal components and those made of metal-ceramic compounds [130]. Based on the two-component injection molding process, it is possible to produce components with a rigid exterior and a tough core. A low-pressure injection molding technique [131] has been used as a method for fabricating ceramic thread-guide components used in the textile industry. Injection molding has great promise for fabrication on the $<100\ \text{nm}$ scale, although the required technology has not yet been developed.

Excimer Laser Micromachining [132, 133] is a technique based on laser ablation. Currently, this process can routinely ablate vias as small as $6\ \mu\text{m}$ in diameter in polymers, glass, ceramics and metals. The minimum size of the features that this method can produce is limited by diffraction and by heat/mass transport. Commercial instruments and services are available from a number of companies (for example, Resonetics, Itek).

Laser Direct Writing is a technique that combines laser-assisted deposition and a high-resolution translational stage to fabricate patterned microstructures from a wide range of materials [134–137]. For example, laser-assisted deposition can be used for generating micropatterns of seeding materials for electroless plating [138]. Laser-assisted polymerization enables the fabrication of patterned microstructures of polymers [139]. Stereolithography, based on laser-assisted processing, can be used to fabricate three-dimensional microstructures [140–142].

LIGA (Lithography, Electroforming, Molding) [143, 144] is a technique that combines X-ray (or synchrotron) lithography, electroplating, and molding for fabricating microstructures with high aspect ratios and relatively large feature sizes ($\sim 10\ \mu\text{m}$). Although the standard equipment for UV exposure can be adapted for this application, special optics and alignment systems are needed for structures thicker than $200\ \mu\text{m}$.

Electrochemical micromachining (EMM) is a technique designed to generate patterned microstructures in metals and alloys [145]. Microfabrication by EMM may involve maskless or through-mask dissolution. Maskless EMM uses the

impingement of a fine electrolytic jet for thin film patterning. Through-mask EMM involves selective metal dissolution from those regions unprotected by a patterned photoresist on the workpiece. The smallest feature that can be achieved using this technique is $\sim 1\text{ }\mu\text{m}$.

Ultrasonic machining, also known as ultrasonic impact grinding, uses ultrasonically induced vibration delivered to a tool to create accurate cavities and channels of many shapes [146]. It can be used to form deep cavities as small as $250\text{ }\mu\text{m}$ in diameter (with an accuracy of $\sim 50\text{ }\mu\text{m}$) in both hard and brittle materials such as glass, quartz, polymers, ceramics and metals. This technique may be useful for fabrication of large masters.

4

Conclusions and Future Directions

Microstructures and systems are typically fabricated from rigid materials, such as crystalline silicon, amorphous silicon, glass, quartz, metals and organic polymers. Elastomeric materials can be used in applications where rigidity is a drawback. We have demonstrated the concepts of elastomeric systems by fabrication of photothermal detectors, optical modulators and light valves. We believe that elastomeric materials will find additional applications in the areas of optical systems, microanalytical systems, biomaterials and biosensors.

Microfabrication is growing in importance in a wide range of areas outside of microelectronics, including MEMS, microreactors, microanalytical systems and optical devices. Photolithography will continue as the dominant technology in the area of microelectronics for the foreseeable future. Photolithography has, however, a number of limitations for certain types of applications, as discussed in Sect. 3.1.

Soft lithography offers a new strategy for microfabrication. Based on SAMs and molding of organic polymers, this set of techniques represents a non-photolithographic methodology for forming micropatterns, microstructures and microsystems of different materials on a range of substrates. Rapid prototyping enhances the utility of soft lithographic techniques and enables the generation of numerous microstructures and systems with feature sizes $\geq 20\text{ }\mu\text{m}$ at low cost. In a research setting, soft lithographic techniques have generated structures with feature sizes as small as 30 nm . The strengths and weaknesses of these developing techniques are still being defined. Their strengths, however, include low cost (capital and operational), the ability to pattern large areas and the ability to generate structures with feature size $\leq 100\text{ nm}$; limitations include the difficulty in achieving high resolution registration and in controlling distortion of patterns caused by deformation of the elastomers. We are beginning to address these issues in our research, and we believe that new materials, designs and configurations will lead to improvement in these areas.

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