3

Rapid prototyping of functional microfabricated devices by soft lithography

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3.1   Introduction

Microfabricated devices are integral to electronics (e.g., transistors and integrated circuits), optics (e.g., polarizers and light-emitting diodes), microelectromechanical systems (MEMS) (e.g., accelerometers and micromirrors), and microfluidics (e.g., systems for protein crystallization and for bioassays). There are four general steps in the fabrication of such devices: (i) fabrication of a master (i.e., the pattern from which replicas are made), (ii) replication of the master, (iii) transfer of the pattern present in the replica into a functional material (polymer, ceramic, metal, or semiconductor) to form a functional microstructure, and (iv) registration of a master (the same one, or a different one) with the functional microstructure to form multi-layered structures. Photolithography – the exposure of a photosensitive material through a photomask – is the conventional technique used to replicate patterns. This technique is highly developed and well-suited for applications in microelectronics.[1] It is, however, limited to materials that are photosensitive, and is only suitable for fabrication on planar surfaces. Soft lithography provides an alternative set of techniques for microfabrication (steps 2–4) that does not have these limitations (although it has others).

Soft lithography is a suite of techniques that uses physical contact between a topologically patterned stamp (or mold) and a substrate for pattern transfer. There are two broad classes of soft-lithographic techniques, those that use a soft (elastomeric) stamp to transfer a pattern into organic materials and onto the surface of metals and ceramics and those that use a hard (rigid) stamp to transfer a pattern into thin layers of (soft) organic materials. This chapter will focus on the first of the two classes, and, more specifically, on the uses of soft stamps (or molds) made of elastomeric organic polymers.

Reviews published previously[2–5] have discussed the details of soft lithography. These techniques have five characteristics that are useful for the microfabrication of functional devices:

1. They are rapid. It often takes less than 24 hours to go from a concept to a prototype device.
2. They are inexpensive – they do not require the use of expensive equipment or infrastructure (e.g., cleanrooms).
3. They allow the patterning of a range of functional materials – metals, polymers, molecules, and biological organisms – directly onto surfaces.
4. They can be used to pattern non-planar surfaces.
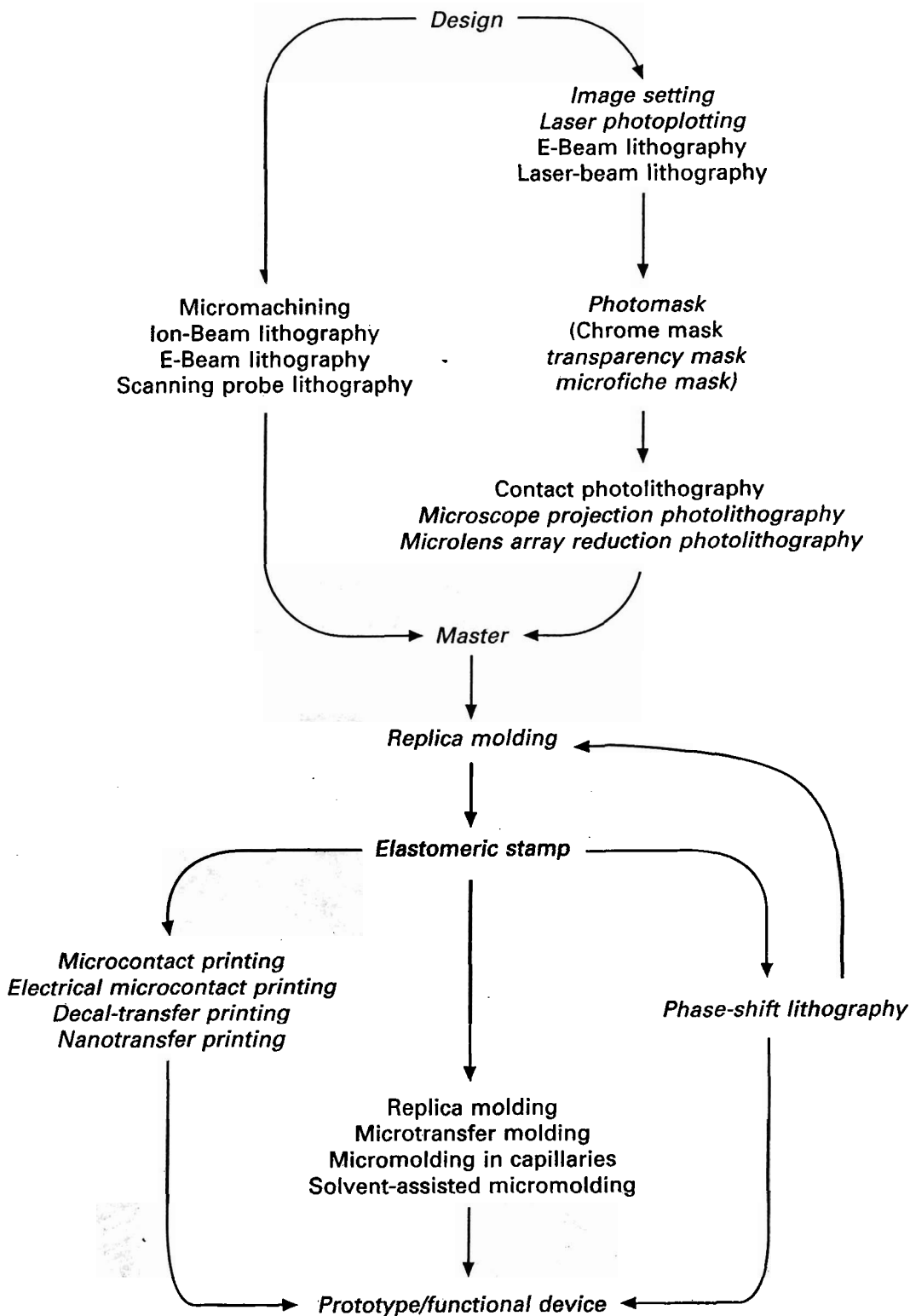5. They are simple to use, and do not require specialized training.

Figure 3.1 diagrams the flow of the process of microfabrication by soft lithography, from the design of the pattern to the generation of the functional device. This chapter will discuss developments in each stage of this process and will also provide examples of devices microfabricated using soft lithography in the period 1999–2004. Examples of the use of soft lithography in **biology,**[6-8] biochemistry,[6-8] and microfluidics[8-15] are discussed elsewhere. Here we limit the examples to optical and electronic microdevices fabricated by printing or phase-shifting photolithographic techniques.

3.2   Developments in soft lithographic techniques

During the period 1999–2004, there have been a number of developments in each stage of the process of fabrication by soft lithography outlined in Fig. 3.1. This chapter emphasizes those developments that have improved the ability to fabricate functional microdevices by soft lithography.

3.2.1   Methods of fabricating masters

A master contains the pattern in bas-relief that is replicated into an elastomeric stamp. The ability to design and fabricate these masters quickly and at low cost facilitates the rapid prototyping of microdevices by soft lithography. The pattern for a master is generated by computer-aided design (CAD). These designs are translated into topographically patterned masters by micromachining[16] or serial lithographic techniques (e.g., e-beam, scanning probe, or ion-beam lithographies) or into photomasks by serial lithographic or photographic (e.g., image setting or laser photoplotting)[17, 18] techniques. Photomasks are used in photolithography to make topologically patterned masters. The processes (e.g., electron-beam and laser-beam lithographies) used to fabricate topographically patterned masters and conventional photomasks (i.e., chromium-coated float glass, also referred to as a 'chrome mask') directly from the CAD design can be slow (days to weeks) and expensive (> $100/in^2), and thus the total number of designs that can be translated into masters using these techniques is limited by time and cost. In contrast, photomasks prepared by image setting or photoplotting provide alternatives to chrome masks that can be produced rapidly (< 24 hours) and

Design

Image setting
Laser photoplotting
E-Beam lithography
Laser-beam lithography

Micromachining
Ion-Beam lithography
E-Beam lithography
Scanning probe lithography

Photomask
(Chrome mask
transparency mask
microfiche mask)

Contact photolithography
Microscope projection photolithography
Microlens array reduction photolithography

Master

Replica molding

Elastomeric stamp

Microcontact printing
Electrical microcontact printing
Decal-transfer printing
Nanotransfer printing

Phase-shift lithography

Replica molding
Microtransfer molding
Micromolding in capillaries
Solvent-assisted micromolding

Prototype/functional device

3.1 Diagram of the flow of the process of microfabrication by soft lithography. The elements and techniques of this process that will be discussed in this chapter are shown in italics.

at low cost (~ \$1/in^2), albeit with feature sizes limited to $\geq$ 8 μm. These qualities are attractive for the fabrication of masters in a number of areas (for example, microfluidics, biology, and optics), and make soft lithography an

especially attractive method for research and development because prototyping usually involves multiple iterative cycles of the process of fabrication from design to prototype. This discussion describes the characteristics of photomasks that can be fabricated by these techniques.

Fabrication of transparency-based photomasks

Photomasks prepared by laser image setting (5,080 dots/inch (dpi); Linotype-Hell Co) have been an important part of soft lithography since their introduction in 1996.[19] The original demonstration of this capability included photomasks prepared on transparency film with features of lateral dimensions ≥ 20 μm and edge resolution of ~1–2 μm (Fig. 3.2(a)).[19] These photomasks can prepare integrated designs over areas of > 500 cm^2 and enable large-area, modest-resolution microfabrication. The minimum lateral dimension was reduced further to ~10 μm, and the edge resolution to ~1 μm, through photographic reduction of the pattern on the transparency[18] (or on paper)[20] onto microfiche (Fig. 3.2(b)). This two-step process yielded small features at the cost of the area that could be patterned. In one experiment, for example, the area of the
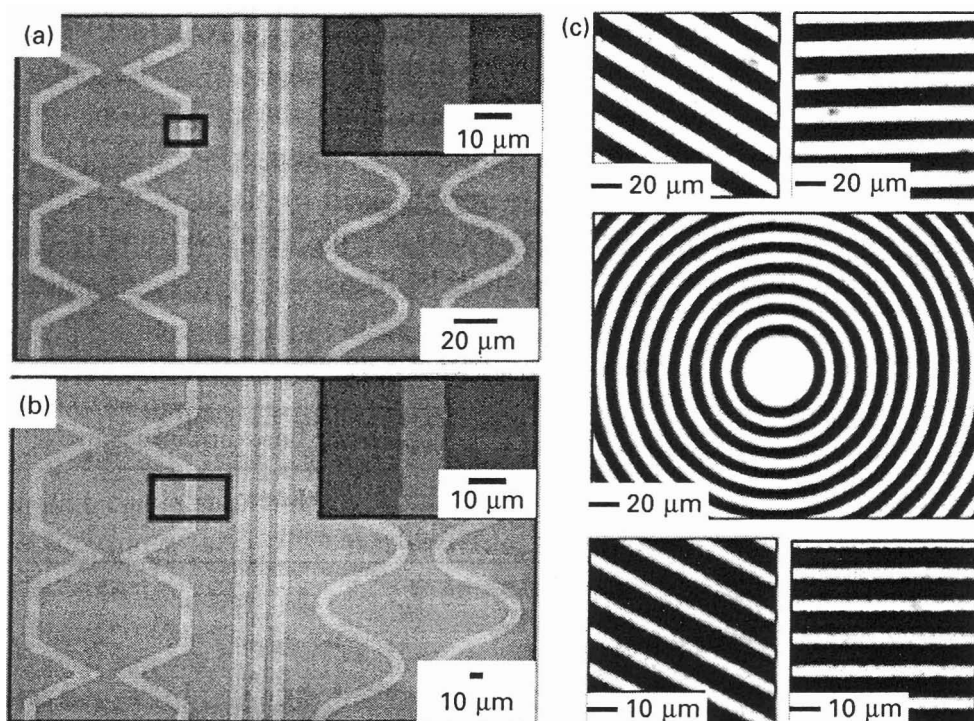
3.2 (a) Optical micrograph of a transparency mask produced by image setting. (b) Optical micrograph of a microfiche mask produced by photographic reduction of (a) by a factor of ~ 25. (c) Optical micrographs of a transparency mask produced by laser photoplotting. The images in (a) and (b) are reproduced with permission from reference 20 (Copyright 2000, American Chemical Society), and the images in (c) are from ref. 17 (Copyright 2003, American Chemical Society).

original transparency was ~560 cm^2 (with minimum feature size of 25 μm) and the area of the microfiche was 19–25 cm^2 (with minimum feature size of 10 μm). A problem with microfiche is poor contrast between the opaque and transparent regions of the microfiche masks, due to the granular nature of the silver grains in the film.[17]

Photomasks prepared by laser photoplotting can have features with lateral dimensions (≥ 8 μm) and edge roughness (~ 1 μm) similar to, or better than, those of microfiche, over large areas (> 500 cm^2) (Fig. 3.2(c)).[17] Laser photoplotting is similar to image setting; each technique is a specialized form of photography. Photoplotters are built for high accuracy and have resolutions of 20,000 dpi; this resolution is four times greater than that of image setters. The cost of photomasks prepared by photoplotting is similar to the cost of those produced by image setting (i.e., < \$0.16/cm^2). Laser photoplotters are available at commercial printing companies in most major cities, and turnaround time for such services is short (~ 1 day).[21] This one-step process has provided a significant improvement in the time and cost required to fabricate high-quality photomasks with sub-20-μm features for use in soft lithography.

Table 3.1 compares the properties of chrome masks to those of transparency-based masks. The ultimate limit of resolution of photomasks prepared by laser photoplotting is determined by two factors, the cross-sectional size of the laser beam and the resolution of the photosensitive films.[17] The wavelength (and thus, the size of the diffraction-limited beam spot) of electron beams is much smaller than that used for laser photoplotting. In addition, the photosensitive materials used in electron-beam lithography (e.g., poly(methylmethacrylate) (PMMA)) have resolutions that are much higher than those of the silver-halide films used in laser photoplotting.

Table 3.1 Properties of chrome and transparency-based masks

	Chrome mask	Transparency-based masks		
		Image setting	Microfiche	Photoplotting
Minimum lateral dimensions (μm)	< 0.5	25	15	8
Edge roughness (μm)	< 0.1	1–2	1	< 1
Advantages	High resolution	Low cost, short turnaround (~1 day)		
Disadvantages	High cost, long turnaround (1–2 weeks)	Medium resolution		

Electron-beam lithography, therefore, is capable of resolutions (< 20 nm) and edge roughness (< 10 nm) that are superior to those of laser photoplotters. Many applications for microfabricated devices (e.g., biology, sensors, microfluidics, and some microelectronics), however, do not require this resolution. Generation of photomasks by laser photoplotting, therefore, provides an attractive, low-cost, and rapid alternative to conventional techniques for the fabrication of masters for use in soft lithography.

Fabrication of photoresist-based masters using transparency masks

Transparency-based photomasks can be used to prepare topographically-patterned masters made of photoresist by three types of photolithography: (i) contact photolithography, (ii) microscope projection photolithography (MPP),[22] and (iii) microlens array reduction photolithography (MAP).[23–25] MPP and MAP are alternatives to contact photolithography that are especially useful in making repetitive micropatterns.

Contact photolithography

Contact photolithography is widely used both in industrial and research settings. This technique generates a master comprising an array of photoresist-based features that form by parallel replication of the features in the photomask in a single exposure over areas as large as $\sim 2 \times 10^4$ mm^2 (150-mm-diameter wafer). It is useful for microfabricating masters with features as large as 10–15 cm (for example, those used to fabricate microfluidic channels). In this technique, a photomask is placed in physical contact with a photoresist-coated substrate, and the photoresist is exposed with UV-light through the photomask. The pattern is developed by dissolving the photoresist in the area that was exposed (positive resist) or the area that was not exposed (negative resist). The use of transparency masks in this process is not operationally different from using conventional chrome masks, so transparency masks integrate easily into existing photolithographic equipment and processes. It is a 1:1 technique and does not provide size reduction, and damage or contamination of the resist layer or the mask are concerns.

Microscope projection photolithography (MPP)

Microscope projection photolithography (MPP)[22] is useful for the fabrication of features smaller than those available by contact photolithography with transparency-based masks (i.e., features with lateral dimensions of $\sim 1–10$ µm), albeit over small areas ($\sim 4 \times 10^4$ µm^2) per exposure. Features on this scale are useful in cell biology,[26, 27] microfluidics,[14] and microelectronics.[28] The technique requires only a standard upright microscope equipped with a

mercury-arc lamp; it is therefore accessible to most research laboratories. MPP includes two features that are common to photolithographic steppers used commercially. First, the translation stage of the microscope allows for accurate registration (< 0.35 μm) of the pattern for multi-level fabrication. Second, multiple copies of the same pattern can be generated on a single substrate by translating (i.e., stepping) the sample and repeating the exposure.

In MPP (Fig. 3.3(a)), a transparency photomask is placed in the light path of an upright microscope at the conjugate image plane to the image plane of the substrate so the two images are in focus at the same vertical location of the translation stage. The optics of the microscope (i.e., the objectives and lenses) reduce the lateral dimensions of the pattern on a transparency photomask projected onto a photoresist-coated substrate.[29] The minimum resolution of the technique, R, is limited by diffraction – that is, $R = K\lambda/2NA$, where $K \approx 1$ for a single-layer resist on a reflective substrate, λ is the wavelength of light, and NA is the numerical aperture of the objective.[30] Figure 3.3(c) shows an example of features prepared by this technique.
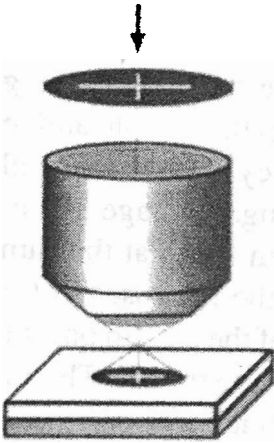
Microlens array reduction photolithography (MAP)

Microlens array reduction photolithography (MAP) is capable of producing a periodic array of patterns with μm-sized features over cm^2 areas.[23–25] The types of patterns generated by MAP are useful for applications in media for data storage and in patterned substrates for biological assays. MAP produces this array in a single exposure, whereas commercial step-and-repeat lithographic techniques require multiple exposures to pattern similar areas. The microlenses are capable of reducing the lateral dimensions of features in a photomask by a factor of $\sim 10^3$ in a single step, to yield features with minimum lateral dimensions of ~ 500 nm.[31] The position of the lens with respect to the light source, as well as the size and shape of the pattern on the transparency-based photomask, determine the extent of distortion in the features produced at the edges of the lens array. These distortions due to edge effects are relatively small for areas of ~ 4 cm^2.

The technique uses an array of microlenses prepared by contact photolithography and reflow of the photoresist,[32] or an array of transparent microspheres,[33] to reduce the pattern from a transparency-based photomask onto a photoresist-coated substrate (Fig. 3.3(d)). The photoresist-coated substrate is positioned at a distance equal to the focal length of the lenses by coating the substrate with a thin layer of poly(dimethylsiloxane) (PDMS) of the appropriate thickness. The conformal contact between the PDMS and the substrate reduces distortions due to tilting of the array with respect to the substrate. The surface that contacts the photoresist is a soft, elastomeric polymer, so neither surface is damaged by contact. Because the PDMS has a low interfacial free energy ($\tau = 21.6$ dyn/cm^2), its surface resists contamination

Microscope projection
photolithography

Projected image
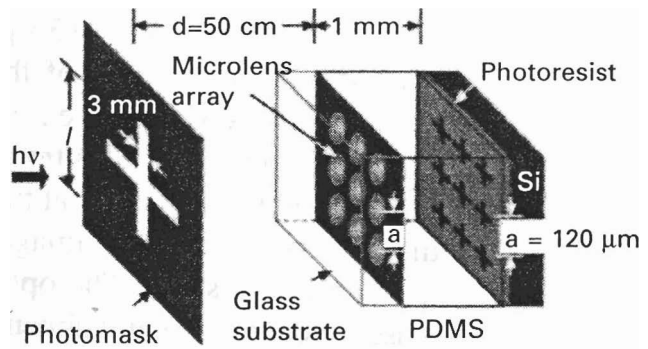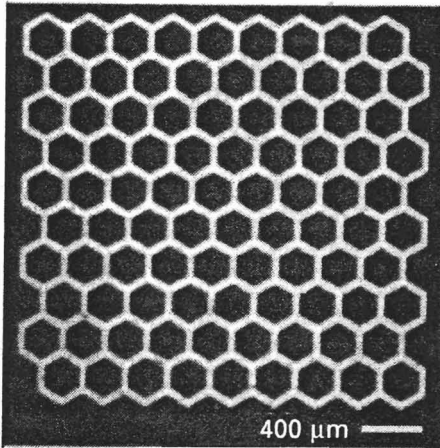
Microlens array reduction
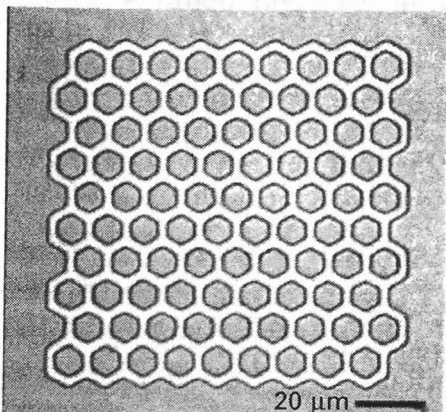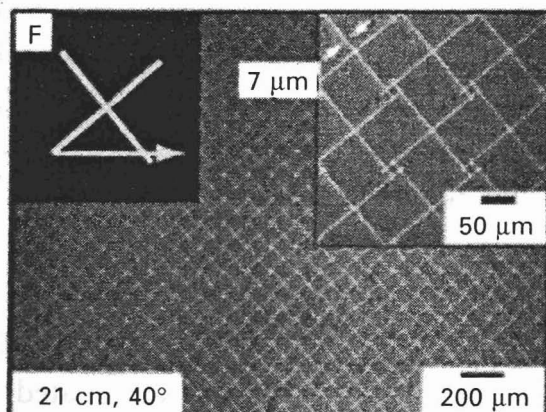photolithography

Photoresist on substrate
(a)

(d)

(b)
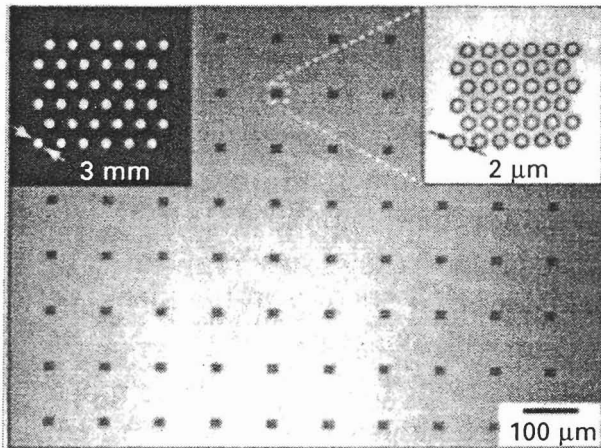
(e)

(c)

(f)

3.3 (a) Schematic diagram of the reduction of an image on a photomask onto a photoresist-coated substrate by MPP. (b) Optical micrograph of a transparency mask prepared by image setting. (c) Optical micrograph of a photoresist pattern produced by MPP using the mask in (b). (d) Schematic diagram of the process of MAP. (e)–(f) Optical micrographs of patterns produced by MPP. The insets are optical micrographs of the masks used to pattern the features in the respective images. The images in figures (a)–(c) are reproduced with permission from ref. 22, the images in (d) and (e) from ref. 23, and the image in (f) from ref. 24 (Copyright 2001 and 2002, American Chemical Society).

and is easy to clean. The exposure of the photoresist through the microlenses can be carried out on a standard overhead projector (or other inexpensive source of diffuse illumination); no additional infrastructure or equipment is necessary for this technique. The features in the array can be discrete[24, 25] or connected[23] depending on the size of the features on the original photomask (Fig. 3.3(e) and (f)). Arrays of features with variable topography and shape can be generated by MAP using grey-scale transparencies.[24] Changing the orientation of the pattern being imaged with respect to the array of microlenses can produce an array of different images from a single pattern.[24]

3.2.2   Types of elastomeric materials used for stamps

Polydimethylsiloxane (PDMS)

PDMS is the elastomeric material most commonly used to make stamps or molds for soft lithography. These stamps are made by replica molding of topographically patterned masters by techniques discussed previously (Fig. 3.4(a)).[2,3,5] In principle, any elastomeric material that replicates the topology of a master may be useful as a stamp.[34] Sylgard 184 (184-PDMS) is an inexpensive commercial brand of PDMS[35] that is used commonly as the material for the stamps.[2, 3] This material works well for most applications in microfabrication requiring replication of masters with features with lateral dimensions of > 500 nm. The replication of features with lateral dimensions < 500 nm with 184-PDMS yields stamps with deformed, buckled, or collapsed features resulting from lateral and/or roof collapse.[36] Deformation and rounding of the edges of the features also occurs due to surface tension (Fig. 3.4(c)).[36] Most of these problems reflect the low elastic modulus of 184-PDMS (1.8 MPa). The development of formulations of PDMS that have elastic moduli greater than that of 184-PDMS – e.g., h-PDMS[37] and hv-PDMS[38] – have enabled replication of sub-100-nm features. Composite stamps made of a thin layer of h-PDMS (40 μm) and a thick layer of 184-PDMS (3 mm) have the ability to replicate sub-100-nm features with the same fidelity as h-PDMS, but are not as fragile as pure h-PDMS replicas (Fig. 3.4(d)).[36] These materials can replicate features with lateral dimensions as small as 30 nm,[36, 37] and vertical dimensions as small as 2 nm (Fig. 3.4(f)).[39] Table 3.2 summarizes the physical properties of these types of PDMS.

Block co-polymers

The use of block co-polymer thermoplastics – e.g., polyolefins,[40] poly(styrene-*block*-butadiene-*block*-styrene) (SBS),[41] and poly(styrene-*block*-ethylene-*co*-butylene-*block*-styrene) (SEBS)[41] – as materials for elastomeric stamps has also been explored. These materials have an elastic modulus higher than that

of 184-PDMS (Table 3.2),[42] and thus replicas of these materials are less susceptible to deformations of the features due to roof or lateral collapse. These stamps are also less fragile (more ductile) than those made of *h*-PDMS. The replicas using these materials, however, are more difficult to prepare than those of PDMS because they require the use of hot embossing techniques that use temperatures of 150–200 °C and loads of 200 g. These conditions are not compatible with most photoresist-based masters.

Hydrogels

Hydrogel stamps are useful as an alternative to PDMS stamps because they are inherently hydrophilic. They are, of course, mechanically fragile, and useful only for certain applications, especially the patterning of proteins and other biologically relevant molecules that are sensitive to their environment. Mayer, *et al.* demonstrated the fabrication of topographically patterned agarose gels by replica molding of a photoresist-based master and of a 184-PDMS replica of this master.[43] Martin, *et al.* formed hydrogels of poly(6-acryloyl-β-*O*-methylcalactopyranoside-*co*-methylele bis(acrylamide) through similar techniques.[44] Hydrogel stamps differ from those made of PDMS or block co-polymers in that hydrophilic molecules dissolve into the bulk of the stamps. This property is useful for uniform patterning of hydrophilic molecules by printing.[43] Hydrophilic molecules also diffuse readily through these stamps. Mayer *et al.* used this capability to create a gradient in the concentration of a protein in the hydrogel stamp and transferred this gradient to a glass slide by printing.[43] Hydrogel stamps must be kept in an aqueous environment to prevent cracking or distortions of the topologically defined features that form as a result of drying out of the stamps.

3.2.3   Replication using elastomeric stamps (soft lithography)

The suite of techniques in soft lithography includes three general types of replication: printing, molding, and phase-shifting lithography. A number of developments in the areas of printing and phase-shifting lithography have extended the capabilities of each of these techniques to include the patterning of hydrophilic and hydrophobic molecules, polymers, proteins, metals, and electrostatic charge on a surface, and the fabrication of features with lateral dimensions < 100 nm.

Microcontact printing (mCP)

Microcontact printing is the process of transferring a material ('ink') from the elastomeric stamp to a substrate when the two are in conformal contact
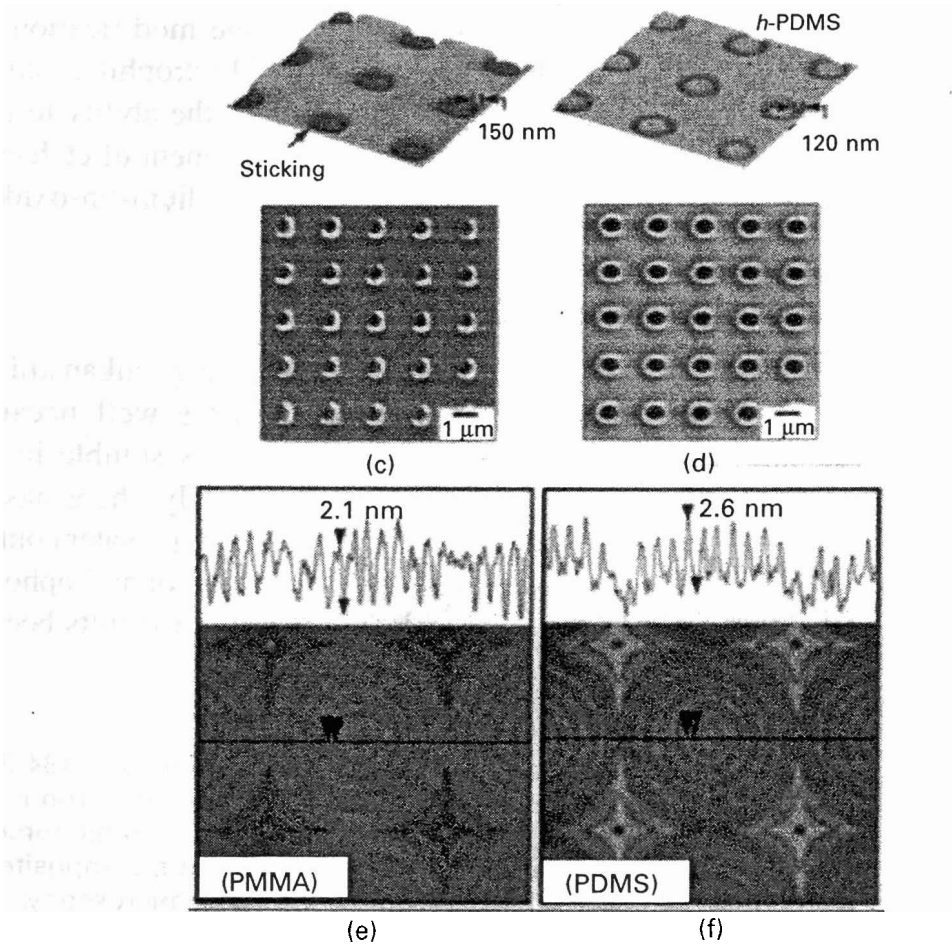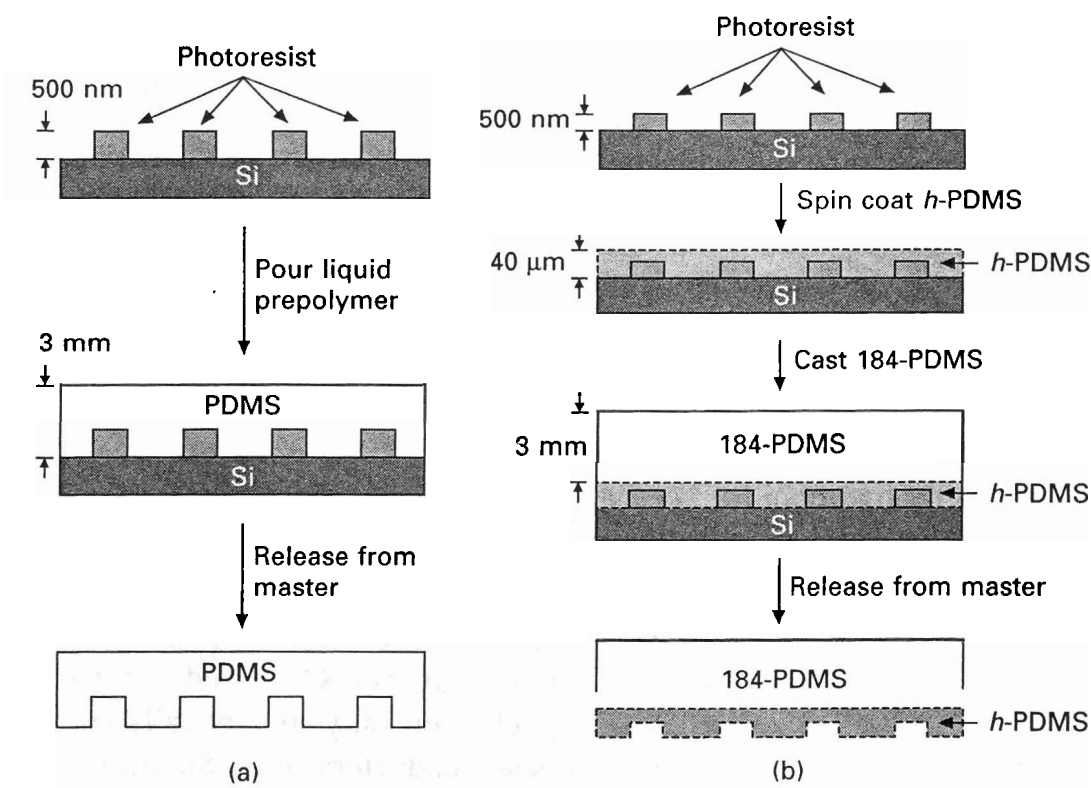
3.4 (a)–(b) Scheme for replica molding of a master into PDMS (a) and into a composite stamp (b). (c)–(d) (top) Atomic force micrograph of

Table 3.2 Physical properties of elastomers used in soft lithography

Material	Tensile modulus (MPa)	Tensile strength MPa)	Surface free energy (dyn/cm^2)	Coeff. of linear expansion (ppm/°C)	Method of curing	Comm. avail.
PDMS						
184-PDMS	1.8[38]	4.77[38]	21.6	260–310	Heat	Yes
hv-PDMS	3.4[38]	0.13[38]	~20	450[38]	UV-light	No
h-PDMS	8.2[38]	0.02[38]	~ 20	300[38]	Heat	Yes
Co-Polymers						
SBS	14.2[41]	~32[42]			N/A	Yes
SEBS	46.7[41]	~31[42]			N/A	Yes

(Fig. 3.5). The ink forms a self-assembled monolayer (SAM) on the surface of the substrates; this transfer is controlled spatially by the topography of the stamp. The combination of μCP of SAMs and wet-chemical etching is used to generate patterns of electronically and optically relevant metals (e.g., Au, Pd, Pt, Ti, Cu, Ag), semiconductors (e.g., Si, GaAs), and insulators (e.g., SiO$_2$, glass). The details of μCP have been discussed previously.[2,3] Developments in this technique include the modification of the surface of PDMS stamps to enable the patterning of hydrophilic inks, the use of high-molecular weight inks for nanofabrication, the ability to pattern and attach molecules covalently to SAMs, the improvement of etch chemistries for Au and Cu, and the patterning of Pd[45–47] and indium-tin-oxide (ITO).[48, 49]

Hydrophilic PDMS stamps

The patterning of hydrophobic molecules (e.g., alkanethiols) by μCP with PDMS stamps made of Sylgard 184 works well because the stamp is hydrophobic, and thus the molecular 'ink' is soluble in the stamp and is distributed uniformly on the surface. Recently, there has been substantial interest in the patterning of hydrophilic inks (e.g., water containing DNA,[50, 51] proteins,[52–55] and polar molecules).[56–60] The use of hydrophobic PDMS stamps to pattern hydrophilic inks by μCP yields poor results because the ink does

(Caption continued from previous page)

the topography of a replica pattern of rings in 184-PDMS (c) and in a composite stamp (d). (bottom) Scanning electron micrographs of polyurethane replicas of stamps. (e)–(f) Atomic force micrograph of the topography of a PMMA master and a composite stamp replica of this master measured by atomic force microscopy. The images in (c) and (d) are reproduced with permission from ref. 37, and the images in (e) and (f) from ref. 40 (Copyright 2002 and 2003, American Chemical Society).

Microcontact printing

PDMS

0.05–5000 µm

Ink

Print

Substrate

50 nm

Si

Etch

Si
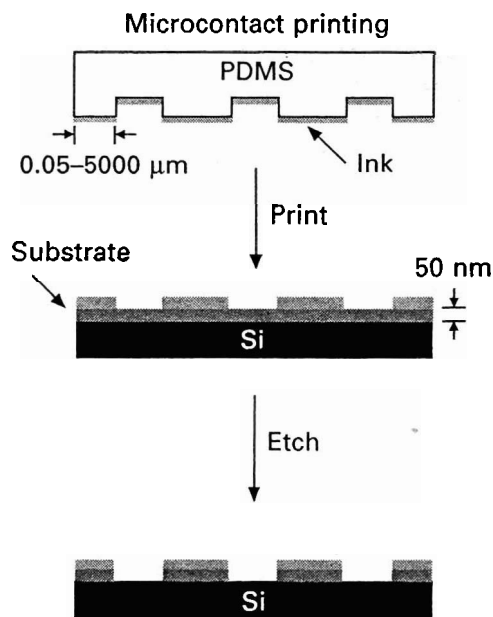
3.5 Scheme for microcontact printing and transfer of the pattern into a substrate by etching.

not coat the surface of the stamp evenly or dissolve into the stamp.[61] Exposure of the PDMS stamps to an oxygen plasma makes the surface of the stamp hydrophilic (by oxidizing Si-CH$_3$ groups to Si-OH, and perhaps Si-CH$_2$-OH groups.[62–64] Reorganization of the surface of oxidized stamps, however, occurs over ~30 min; this reorganization (sometimes called 'reconstruction') causes the surface to revert from hydrophilic to hydrophobic (Fig. 3.6(b)).[61] It probably originates in the migration of mobile, uncrosslinked siloxane molecules from the interior of the polymer to its surface. This reversion can be slowed and minimized by immersing the stamps in water immediately after oxidation.[61–64] Grafting hydrophilic molecules (aminoalkylsilanes)[65] and polymers (e.g., poly(ethyleneoxide)[66] and poly(ethylene glycol)[61] to the surface of oxidized PDMS stamps results in hydrophilic stamps that are stable for > 7 days (Fig. 3.6(c)).

Molecular 'inks'

The ability to control the wettability of the surface of PDMS stamps has expanded the number and types of molecules that can be patterned by µCP. Table 3.3 contains a list of these molecules, and of compatible substrates, for use in µCP.[67–107] Whereas microfabrication of features with lateral dimensions > 500 nm with these inks is relatively simple, fabrication of features < 200 nm is difficult because low molecular-weight (< 0.3 kD) inks (e.g., alkanethiols) diffuse laterally during printing. Li *et al.* addressed this problem by using dendrimer-based inks.[108] Liebau *et al.* used high-molecular weight (> 1000 kD) inks based on thioether-calixarene derivatives.[105] These inks exhibit low
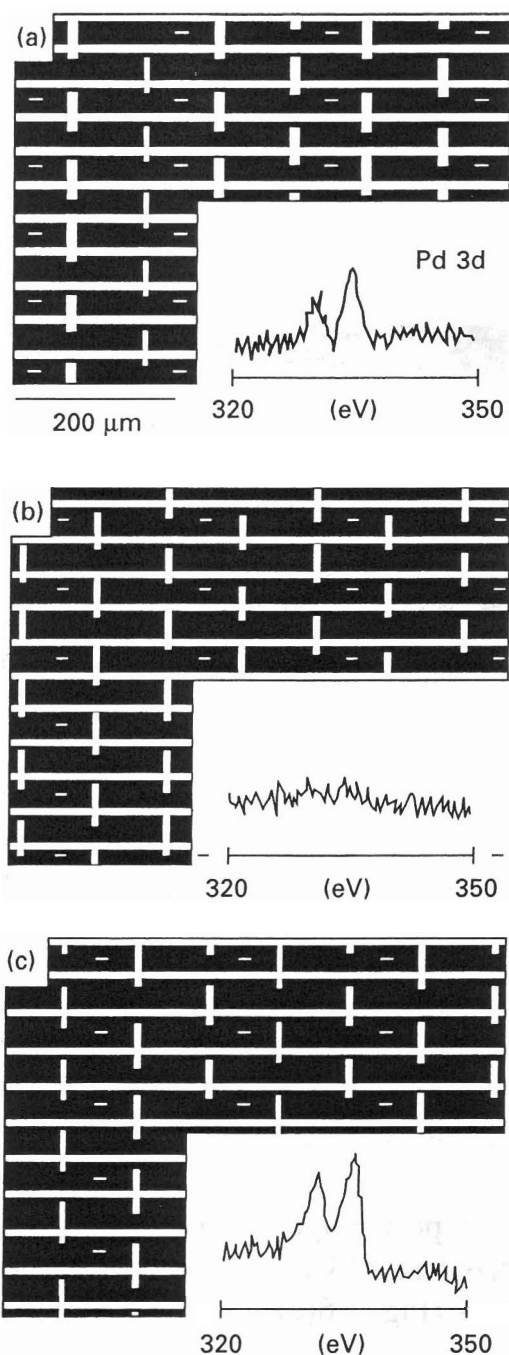
3.6 Patterning using hydrophilic PDMS stamps. A catalyst for the electroless deposition of Cu was patterned by mCP using a freshly oxidized stamp (a), an oxidized stamp 3 h after the plasma treatment (b), and a 20-day-old stamp with a grafted layer of poly(ethylene glycol) (c). The images are scanning electron micrographs of Cu that were electrolessly deposited onto the patterned catalyst. The insets are X-ray photoelectron spectra of the Pd^{2+} catalyst present on the stamp before printing. The images are reproduced with permission from ref. 62 (Copyright 2001, Wiley-VCH).

diffusivity, and thus allow the fabrication of features as small as 40 nm by µCP with composite PDMS stamps (Fig. 3.7).

Table 3.3 Types of ink molecules used in μCP

Ink (headgroup)	Substrates	References
ROH	Si-H	67, 68
	Si	69
RNH_2	Stainless Steel 316L	70
	Mica	71
RSH	Au	72
	Ag	73
	Cu	74
	Pd	75
	Pt	76
	Ni	77
	Stainless Steel 316L	78, 70
	Zn	79
	ZnSe	80
	GaAs	81, 82
	InP	83
RSeH	Au	84, 85
	Ag	86
$RS_2O_3^-Na^+$	Au	87
	Cu	88
$RCOO^-/RCOOH$	$\alpha\text{-}Al_2O_3$	89
	Ti/TiO_2	90
$RSiX_3$	Al/Al_2O_3	91
X=H, Cl, OCH_2CH_3	Si/SiO_2	92
	TiO_2	93–95
	ZrO_2	93, 95
	HfO_2	95
	PtO	96
	Indium tin oxide (ITO)	48
$RPO_3^{2-}/RP(O)(OH)_2$	Al	97, 98
	Al-OH	99
	TiO_2	94, 90
	ZrO_2	100, 101
	GaAs	102
	GaN	102
	Mica	103
	Tooth enamel	104, 105
	Indium tin oxide (ITO)	49
	Indium zinc oxide (IZO)	49
RPO_3^{2-}	TiO_2	106–108
	Nb_2O_5	108
	Al_2O_3	108

Conductive substrate materials

SAMs patterned by μCP can act as resists to wet-chemical etchants; this capability is the basis for patterning thin films of metals, semiconductors, and insulators for use in microelectronic devices; examples include wires or
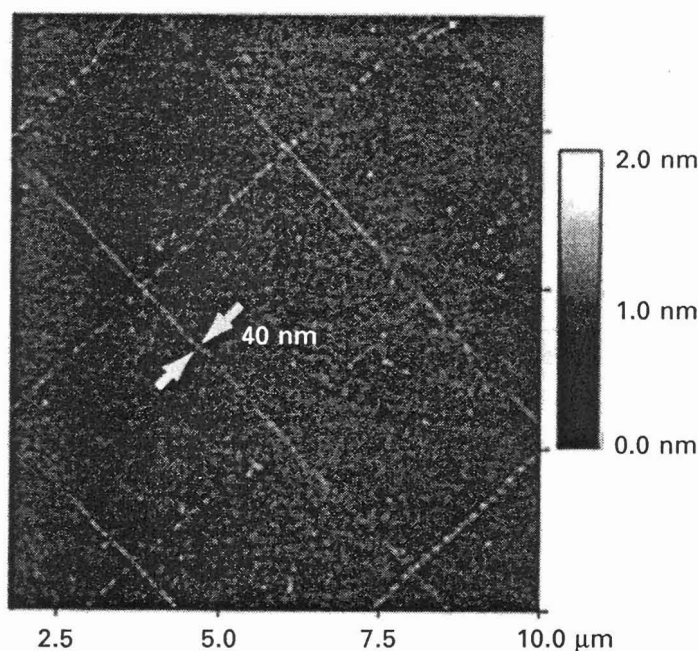
3.7 Atomic force micrograph of lines of dendrimers printed by two separate mCP steps; the stamp was rotated by 90° for the second step. These lines do not appear to be continuous. The image is reproduced with permission from ref. 106 (Copyright 2003, American Chemical Society).

contacts.[2, 3] Table 3.4 lists metals and conductive oxides used for this purpose along with wet-chemical etchants that are compatible with SAMs for microfabrication.[94, 106, 107, 109–112] The coinage metals (Au, Ag, and Cu) are used commonly as substrates for this purpose.[2, 3]

Defects in the metallic film after etching is a problem common to patterning by μCP on these metals, and can hinder performance of microelectronic

Table 3.4 Types of conductive films, and etchants used with these films

Surface	Etchant	References
Au	$K_3Fe(CN)_6/K_4Fe(CN)_6/Na_2S_2O_3/KOH$	107
	$FeNO_3$/thiourea	94
Ag	$K_3Fe(CN)_6/K_4Fe(CN)_6/Na_2S_2O_3$	107
	$FeNO_3$/thiourea	94
Cu	$FeCl_3$/HCl or NH_4Cl	109
	H_2O_2/HCl	110
	KCN/NaOH/KCl	106
	3-nitrobenzene sulfonic acid/ poly(ethylene imine)	106
	$FeNO_3$/thiourea	94
Pd	$FeCl3$	45, 46, 111
	$FeNO_3$	94
Pt	HCl/Cl_2	94, 112
Indium tin oxide	Oxalic acid	49
Indium zinc oxide	Oxalic acid	49

devices fabricated by these techniques. Geissler *et al.* used two techniques to decrease the number of defects in patterns of Au and Cu formed by μCP and wet-chemical etching.[106] First, they added octan-1-ol to the etch solution for Au to fill in defects in the SAM of alkanethiolates formed by μCP (Fig. 3.8(a)). Use of this additive significantly reduced the density of etched pits in the patterned thin film of Au (Figs. 3.8(b) and (c)). Secondly, they used a solution containing 3-nitrobenzenesulfonic acid (NBSA) and branched polyethylenimine (PEI) to etch copper patterned by μCP with a SAM of alkanethiolates. They hypothesized that the large molecules of the etch solution could not penetrate through the defects in the SAM, and etching thus produced high-quality patterns of Cu (Figs 3.8d–f).
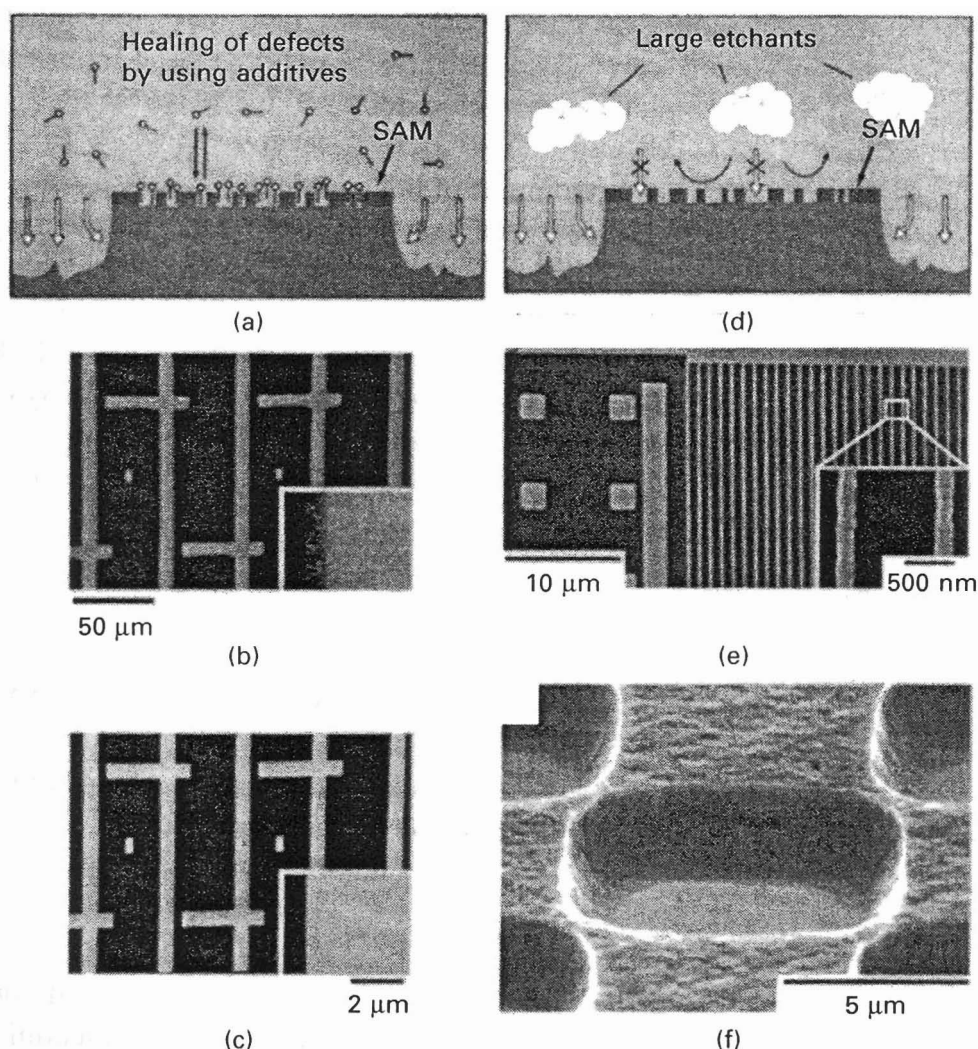
3.8 (a) Schematic diagram of the 'healing' of defects in SAMs using additive molecules such as octanol that have high affinity for the SAM, but not for the surface. (b)–(c) Au surface patterned by mCP of ECT and etched without (b) and with (c) octanol in the etch solution. (d) Schematic diagram of the use of large wet-chemical etchants that cannot fit into the defects in the SAM. (e)–(f) Cu surface patterned by mCP of ECT and etched with the PEI/NBSA solution. All of the images are reproduced with permission from ref. 108 (Copyright 2002, American Chemical Society).

Love *et al.*, showed that Pd features generated by μCP of alkanethiols and wet-chemical etching were less rough (by a factor of five) and had fewer defects (by a factor of ~100) than those produced on gold (Fig. 3.9(b)).[45–47] These improvements in the quality of the metallic features result in part from the presence of a thin PdS layer below the SAM of alkanethiolates (Fig. 3.9(a)). This layer acts as an added resist to wet-chemical etchants. Pd has four additional properties useful for microfabrication of functional devices: (i) It resists oxidation in air below 400 °C. (ii) It absorbs 900 times its volume (at STP) in hydrogen – this property is the basis for hydrogen sensors (Figs 3.9(d)–(f)).[45] (iii) It is compatible with materials used in CMOS processing. (iv) It has a wide variety of useful activities as a catalyst.

Two groups have extended μCP techniques to the patterning of transparent conductive oxides;[48,49] these materials are used commonly in light-emitting devices and liquid-crystal displays as a transparent electrode. Breen *et al.* used alkanephosphonic acids as the ink in μCP to pattern indium-tin-oxide (ITO) and indium-zinc-oxide (IZO).[49] Although this system was capable of patterning features with lateral dimensions as small as 2 μm, there were numerous etched pits present throughout the sample. Koide *et al.* improved the quality of these features by printing alkyltrichlorosilanes on ITO at elevated temperatures (50 °C).[48] The elevated temperature was necessary to increase the rate of reaction of the silane with the ITO. These SAMs were used as insulating layers in organic light-emitting display (OLED) devices with pixels of 1 μm diameter.[48] They do not etch the unprotected regions of the ITO, and thus a direct comparison of the limits of resolution of this technique to that of Breen *et al.* is not possible.

New variations on μCP

There are a number of variations of μCP that provide new capabilities, such as transferring metallic films, storing of charge, and bleaching of dyes. These abilities and developments are the basis for the microfabrication of a number of devices included in this discussion.

Patterning of reactive SAMs

Lahiri, *et al.* developed a method to pattern ligands onto self-assembled monolayers formed on Au by μCP.[113] This technique is useful for patterning biologically relevant ligands onto surfaces that resist protein adsorption. These patterned surfaces are useful for bio- and cell-based assays.[6] In this technique, a ligand that contains a nucleophilic amine is transferred to a SAM formed on Au that has a reactive terminal group. The SAM comprised a small mole fraction (< 0.1) of a pentafluorophenol-activated, terminal carboxylic acid group and a terminal tri(ethyleneglycol) group; the triethylene
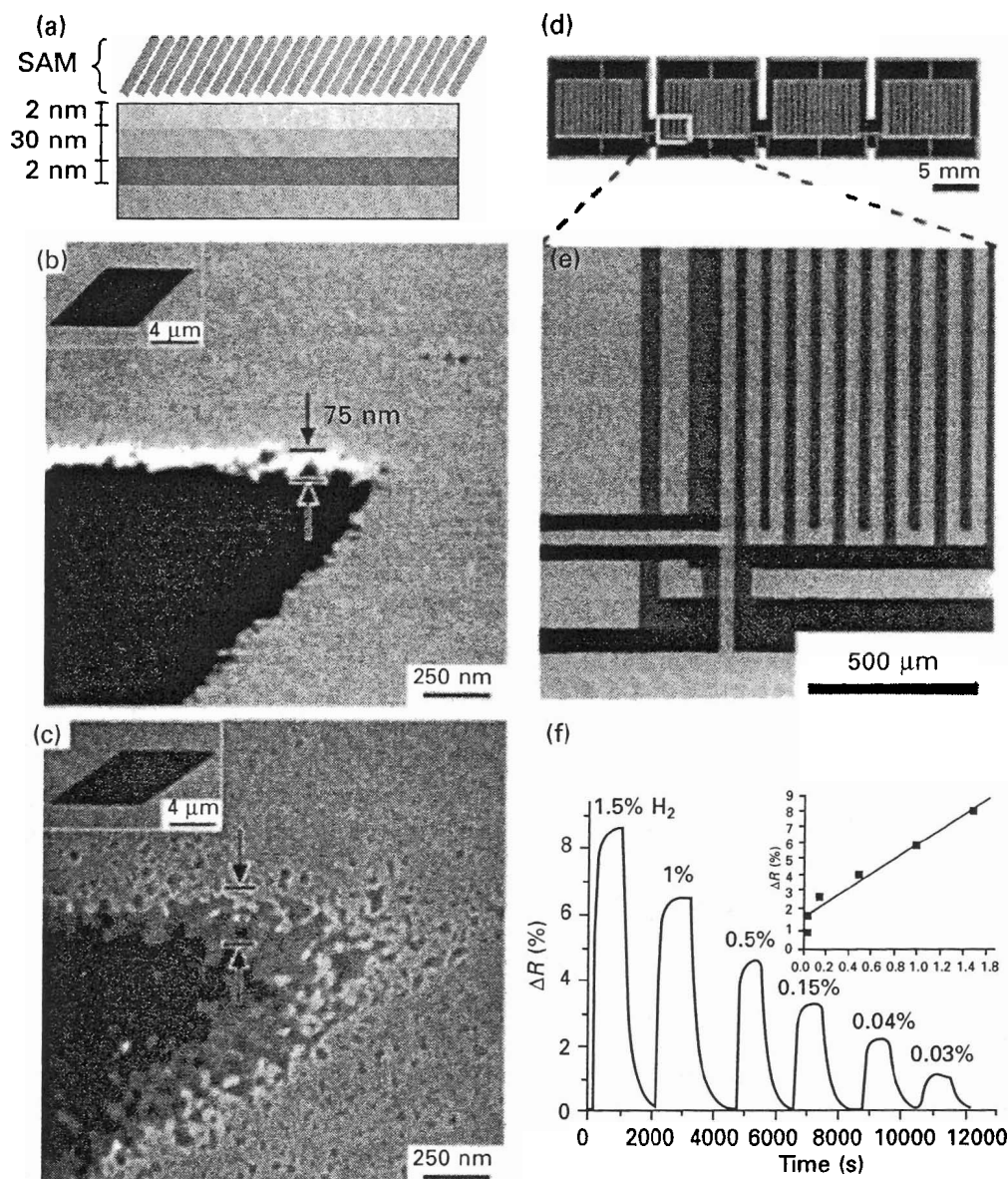
3.9 (a) Schematic diagram of SAMs of alkanethiolates formed on Pd. (b)–(c) Scanning electron micrographs of features patterned in Pd (b) and Au (c) by mCP of octadecanethiol. (d) Design of a 2-m long serpentine wire with electrical contacts positioned along the length of the wire to facilitate measurement of the electrical properties as a function of length. (e) Scanning electron micrograph of a section of the wire fabricated by mCP and wet-chemical etching. (f) Plot of the change in resistance as a function of time on exposure of a microfabricated wire to concentrations of H_2 ranging from 0.03–1.5% vol. in N_2. The inset is a plot of the change in resistance as a function of the concentration of H_2. The images in (b) and (c) are reproduced with permission from ref. 47 (Copyright 2002, American Chemical Society) and the images in (d)–(f) from ref. 46 (Copyright 2002, American Institute of Physics).

glycol was present to resist the non-specific adsorption of proteins on the surface. An oxidized stamp was inked with a ligand and placed in contact with the mixed-SAM-coated Au substrate. The reaction of amine-terminated

ligands with the activated carboxylic acid group occurred with high yield (~75–90%).[113] This technique is one example of the patterning of reactive SAMs. Reviews by Kane et al.,[7] Sullivan and Huck[114], and Chechik et al.[115] describe additional examples of work in this area.

Positive microcontact printing ((+)-μCP)

Delamarche et al. developed a technique for generating a positive replica in metal of the master from which the PDMS stamp was prepared (Fig. 3.10(c)); that is, this technique is used to produce the inverse pattern of that generated by standard μCP (Figs 3.10(a) and (b)).[116] This process is useful for generating metallic replicas of features with lateral dimensions < 1 μm. By contrast, the use of 184-PDMS stamps with raised features of these dimensions in μCP results in unwanted contact of the stamp with the substrate because of roof collapse.[36] In (+)-μCP, pentraerythritol-tetrakis(3-mercaptopropionate) (PTMP), which is used as the ink, is printed onto the surface of Au and Cu. This monolayer passivated the surface of the metal and prevented binding of other alkanethiols. A SAM of eicosanethiol (ECT) was formed in the unpatterned region. The SAM of ECT acted as a barrier to wet-chemical etchants, whereas the SAM of PTMP was not resistant because it does not form a well-packed monolayer. Figure 3.10(d) shows features generated in Au thin films by (+)-μCP.
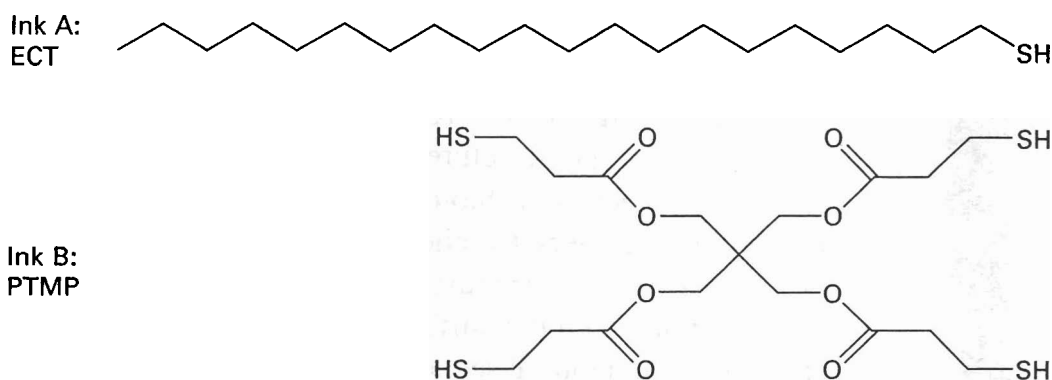
Chemically-amplified soft lithography

Yu et al. described a technique for patterning a conductive polymer by μCP that is useful for fabricating polymer-based microelectronic devices.[117] In this technique, camphorsulfonic acid was used as the ink and was transferred by μCP using a topographically patterned 184-PDMS stamp onto the surface of a thin film (90 nm) of a poly(thiophene)-derivative containing tetrahydropyranyloxyalkyl side chains (Fig. 3.11(a)). An acid-catalyzed reaction occurred in the regions of contact between the stamp and the polymer film (where the ink was deposited) when the sample was heated to 130 °C for ten seconds. This reaction removed the tetrahydropyran group from the poly(thiophene) to make the solubility of these regions orthogonal. This approach was used to pattern polymeric wires of ~ 100 μm in width (Fig. 3.11(c)); it may be difficult to pattern features of < 5 μm in width because of diffusive spreading of the acidic ink. The ultimate limit of resolution of this technique has not been defined.
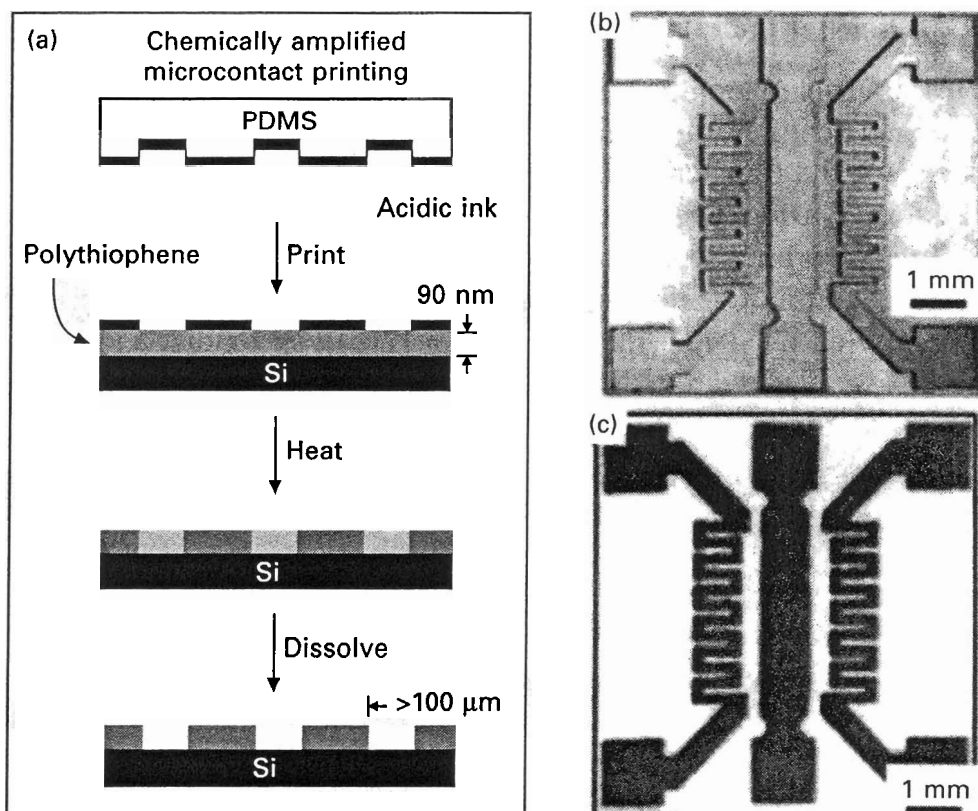
Elastomeric membrane printing (EMP)

Lift-off is a technique that is used commonly to pattern metals in the

3.10 Comparison of patterning Au by standard mCP ((a) and (b)) and by (+)-mCP ((c) and (d)). The image in (b) is reproduced with permission from ref. 108, and (d) from ref. 117. Copyright 2002, American Chemical Society.

3.11 (a) Scheme for chemically amplified soft lithography. (b) Optical micrograph of the topographically patterned PDMS stamp used to pattern the polymer. (c) Optical micrograph of the polymer after patterning and dissolution of the unpatterned regions. The images in (b) and (c) are reproduced by permission of The Royal Society of Chemistry from ref. 118.

semiconductor industry. This process involves three steps: (i) fabrication of a patterned surface of photoresist by photolithography; (ii) evaporation of metal onto this patterned surface; (iii) removal of the photoresist, and the metal deposited on top of the features defined in the resist, using organic solvents. Many materials (e.g., biological organisms, proteins, and some polymers) are not compatible with these solvents, and thus cannot be patterned by lift-off. EMP uses PDMS membranes both as a dry resist (for electrodepositing metals, reactive ion etching of silicon, and fabricating hydrogel and sol-gel structures) and as a template for dry lift-off (for patterning metals by evaporation, biological materials by nonspecific adsorption, and conductive polymers by chemical vapor deposition) (Fig. 3.12(a).[118] The entire process is dry because no solvents are necessary to deposit or remove the membrane from the surface. In EMP, the membrane must be continuous (or at least continuous in sections) and mechanically stable. There are, therefore, limitations to the types of pattern that EMP can produce: they must have lateral dimensions > 1 μm, and continuous patterns.
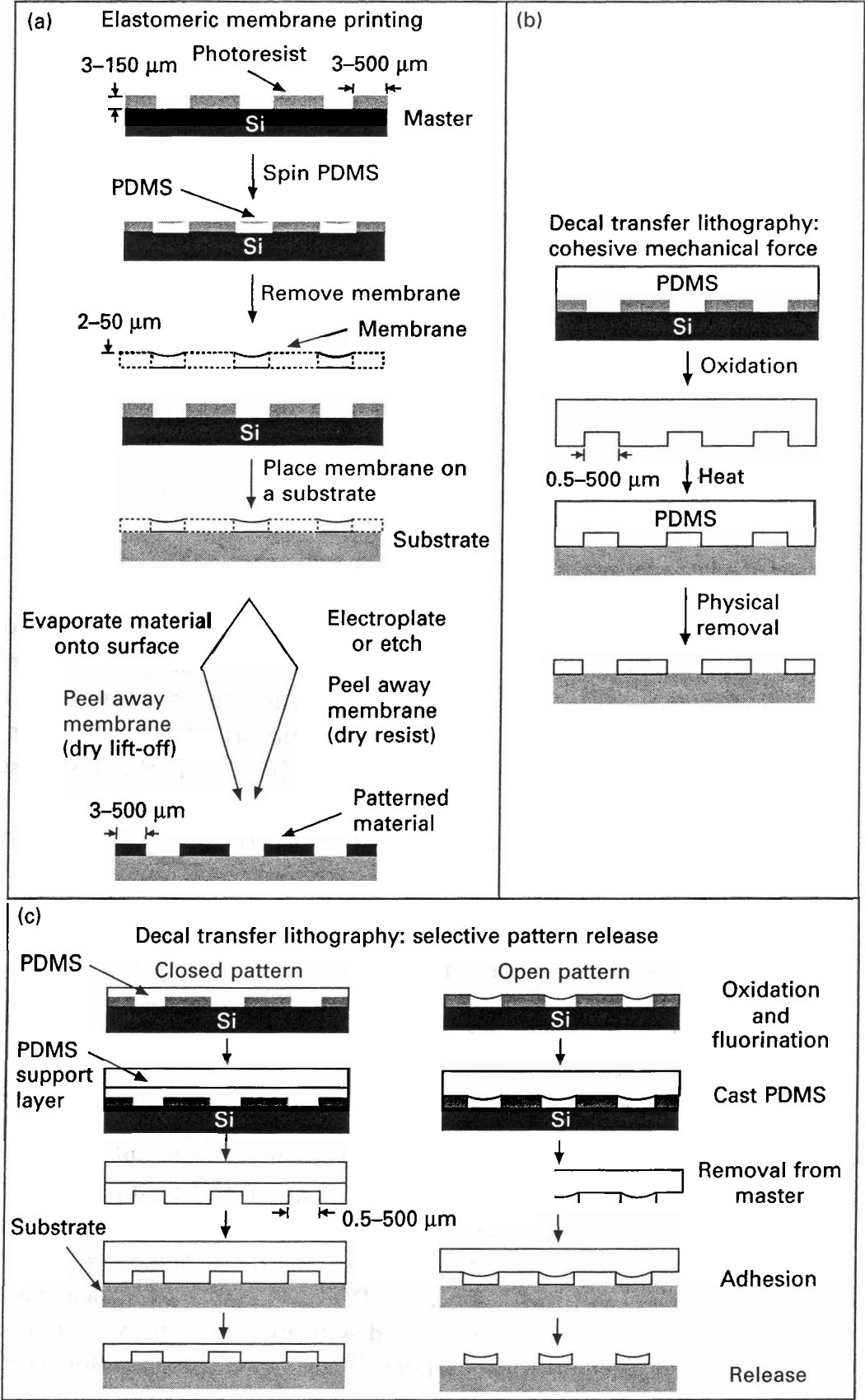
Decal-transfer microlithography (DTM)

Decal-transfer microlithography[119] is a technique that prints the topographically patterned features of a PDMS stamp onto a substrate. This technique is useful for the transfer to surfaces of PDMS-based features that can not be transferred using EMP techniques, e.g., features with lateral dimensions < 1 μm and with discontinuous designs. There are two types of process used to facilitate this transfer, cohesive mechanical failure (CMF) and selective pattern release (SPaR). In CMF (Fig. 3.12(b)), an oxidized PDMS stamp is placed in contact with a silicon, glass, quartz, PDMS, or metal oxide substrate. The surface of the oxidized PDMS stamp bonds irreversibly to these substrates. The PDMS stamp is physically torn from the surface, leaving behind the PDMS that was bound to the surface in the pattern of the topology of the stamp. This technique fabricates patterns that are 'open' – i.e., the individual pieces of PDMS need not be connected by a continuous top layer. Open features are useful as resists to etching of the underlying substrate.

In SPaR (Fig. 3.12(c)), a two-layer PDMS stamp is prepared that has a bottom layer containing the topographical pattern and a top surface that is a removable support layer. The layers can be separated without causing damage to either layer because they are sealed reversibly by van der Waals interactions. This technique can be used to fabricate both 'open' and 'closed' features. Closed features are useful as microfluidic channels or for patterning by micromolding in capillaries (MIMIC).[14] SPaR is less destructive than CMR to the PDMS stamp, but requires two steps of curing PDMS in order to prepare the transfer element. Either process can be repeated to fabricate 3D structures, such as microfluidic networks.[119]

Nanotransfer printing (nTP)

Nanotransfer printing is a method for depositing thin films of gold from a topographically patterned stamp onto the surface of metals, semiconductors, and insulators (Figs 3.13(a) and (b)).[120–123] This technique is additive, that is, the gold features are transferred directly from the PDMS to the substrate, and no additional steps (e.g., wet-chemical etching or dissolving of photoresist) are necessary. Such conditions are useful for the fabrication of contacts for plastic electronics because nTP does not subject the substrate to conditions that may damage the polymer. In this technique, a thin (20 nm) gold film is deposited directly onto a PDMS stamp by physical vapor deposition. The substrate is functionalized with mercaptopropytrimethoxysilane (MPTMS) (for metal oxides or silicon)[120] or 1,8 octadecanedithiol (for non-oxide forming metals or semiconductors, e.g., Au or GaAs);[123] these molecules form a monolayer on the surface that present a terminal thiol group. A covalent bond forms between the gold and the thiol group when the gold-coated stamp is placed in conformal contact with the thiol-presenting surface. The

3.12 Schematic diagrams for (a) elastomeric membrane patterning and ((b) and (c)) the two types of decal transfer lithography.

thin film of gold transfers easily to the substrate because the strength of interaction between it and the thiol-presenting SAM on the substrate is much greater than that of the Au and the PDMS. This technique yields high-quality gold features with lateral dimensions as small as ~100 nm, and edge roughness of ~15 nm (Fig. 3.13(c)). The topology of the stamp can be designed such that a continuous gold film is formed on the surface by physical vapor
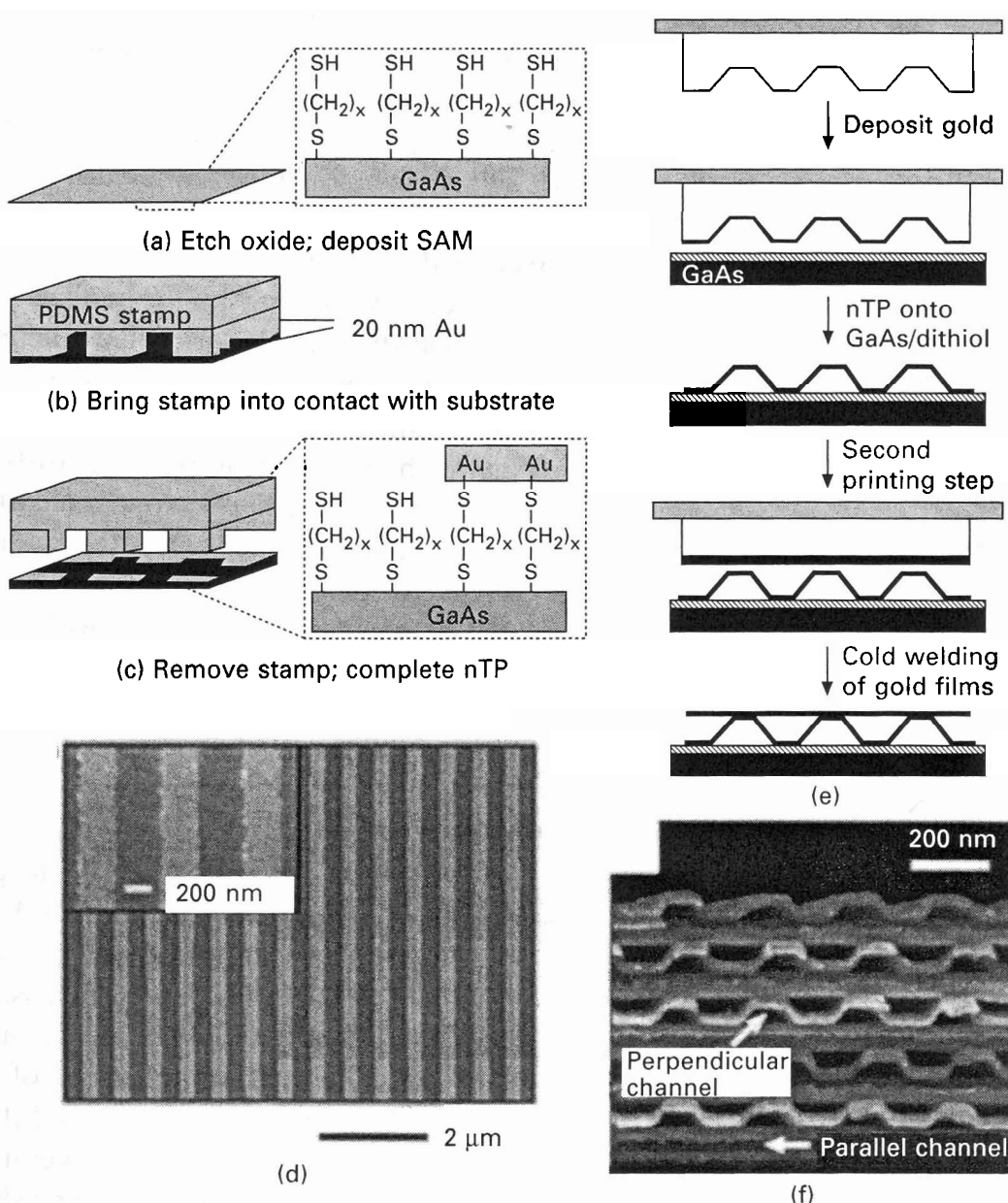
3.13 (a)–(c) Schematic diagram outlining the fabrication of metallic contacts on GaAs by nTP. (d) Scanning electron micrograph of lines of Au patterned on GaAs by nTP. (e) Schematic diagram showing fabrication of three-dimensional structures by nTP. (f) Scanning electron micrograph of a three-dimensional structure fabricated by nTP. The images in (a)–(d) are reproduced with permission from ref. 123, and the images in (e) and (f) from ref. 121. Copyright 2003, American Chemical Society.

deposition. The subsequent transfer of this film by nTP yields a pattern of gold with 3D topology (Fig. 3.13(d)).[103] This technique was used to prepare electrical contacts for high-mobility transistors and inverter circuits.[120, 122]
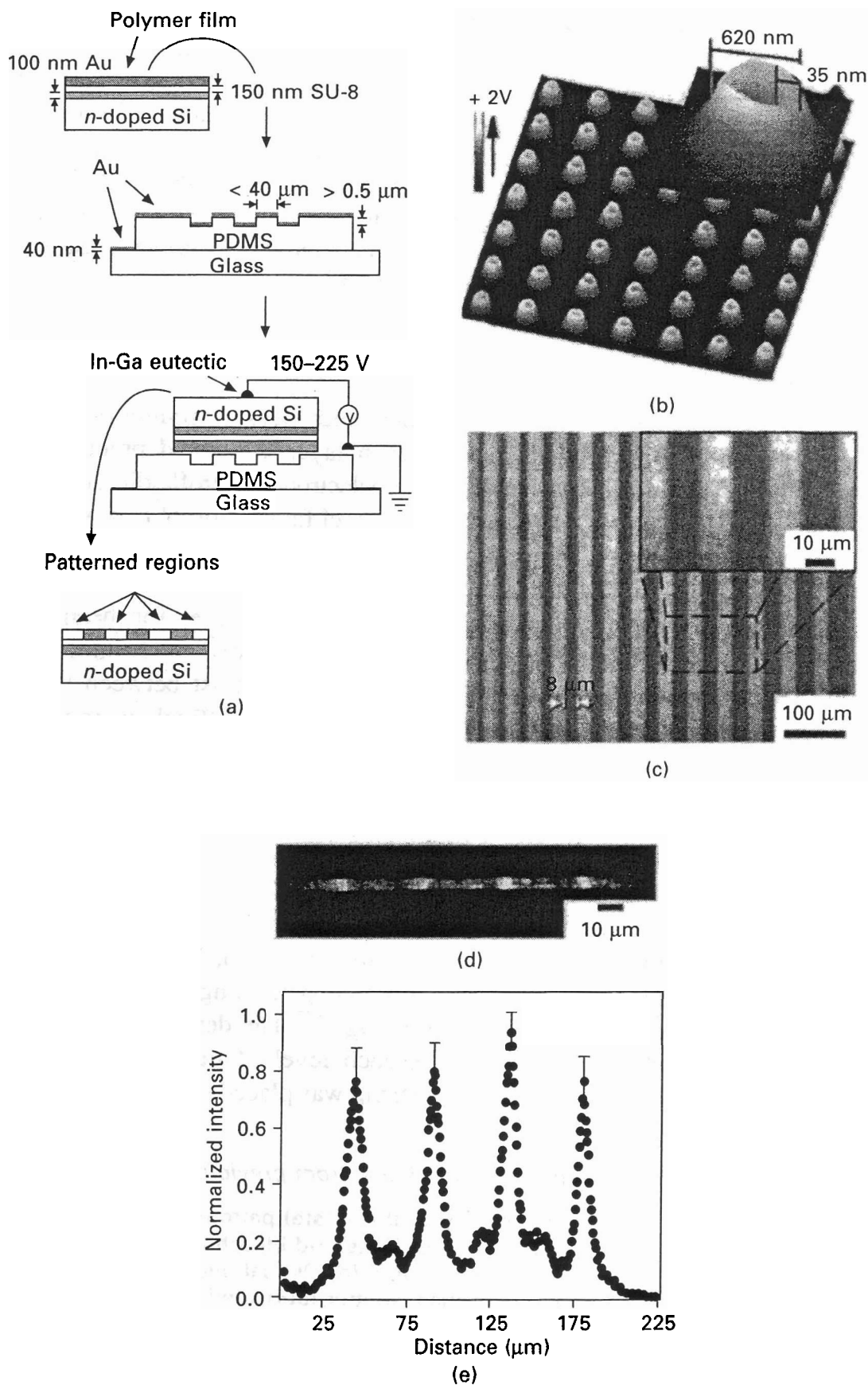
Electrical microcontact printing (E-mCP)

This technique uses a metal-coated, topographically patterned PDMS stamp to define regions of charge[124] or of bleached dyes[125] in polymeric thin films. The patterns generated by this technique may be useful in data storage, and in the fabrication of optical waveguides. Figure 3.14(a) illustrates this process. The metal-coated stamp was prepared by physical vapor deposition of Au onto the PDMS stamp. The stage holding the stamp must be cooled to prevent unwanted thermal expansion of the PDMS during deposition, because this behavior can induce cracks and waves in the thin metallic films upon cooling.[126] The metallic stamp was placed in contact with the surface of a polymer film supported by a conductive substrate (e.g., Au-coated silicon wafer). A DC-bias was applied between the stamp and the substrate such that current flowed through the polymer film. Jacobs, *et al.* used this technique to pattern charge in thin films of poly(methylmethacrylate) (Fig. 3.14(b)).[124] We described the use of this technique to bleach selectively a dye, phloxine B, doped in a thin film (3–5 μm) of poly(vinylphenol) (Fig. 3.14(c)).[125] The bleaching of the dye results in a decrease of the refractive index of these regions. This work is the basis for the fabrication of planar optical waveguides and a 1 × 4 optical splitter (Figs 3.14(d) and (e)).

Phase-shifting photolithography

Features with lateral dimensions of < 100 nm are useful for applications in data storage and subwavelength optics. It is difficult to produce features of this size by standard photolithographic techniques because of limits determined by the numerical aperture of imaging optics. Phase-shifting lithography is a specialized type of photolithography that uses the modulation of the intensity of light in the near field at the edges of features defined in a photomask to pattern features with lateral dimensions of < 100 nm.[127,128] The use of rigid masks in phase-shifting lithography is difficult because the distance between the phase mask and the photoresist layer must be controlled precisely, and because accidental contact between the mask and the layer of resist damages both.

Elastomeric phase masks are a useful alternative to rigid phase masks because the distance between the mask and the substrate is controlled by the height of the features rather than by specialized positioning equipment (Fig. 3.15(a)), and because physical contact is 'soft', and non-damaging. The conformal physical contact between the PDMS mask and the resist also

Polymer film

100 nm Au

150 nm SU-8

n-doped Si

Au

< 40 μm   > 0.5 μm

40 nm

PDMS

Glass

In-Ga eutectic   150–225 V

n-doped Si

PDMS

Glass

Patterned regions

n-doped Si

(a)

+ 2V

620 nm

35 nm

(b)

10 μm

3 μm

100 μm

(c)

10 μm

(d)

(e)

3.14 (a) Scheme for E-mCP using metal-coated PDMS stamps.
(b) Kelvin force micrograph of charge in a film of

minimizes diffractive broadening of features, and allows the generation of small (< 50 nm) features. Rogers *et al.* demonstrated that topographically patterned 184-PDMS stamps can be used as phase masks in photolithography to produce features with lateral dimensions of ~ 100 nm over large areas (> cm^2) rapidly (< 1 s/exposure).[127, 128] Odom *et al.* used an elastomeric phase mask made of a composite 184-PDMS/*h*-PDMS stamp to extend the resolution of this technique to ~ 30 nm (Figs. 3.15(c) and (d)).[36, 129] Phase-shifting photolithography has been used to fabricate transistors (Fig. 3.15(d))[130] and polarizers (Fig. 3.15(e)).[131]

3.2.4   Approaches to registration

The fabrication of complex microdevices requires multiple steps of lithography where the pattern in each layer is aligned precisely in register with the previous ones. Many microelectronic, microfluidic, and microelectromechanical systems require the multilevel fabrication of two or more types of structure. In soft lithography, it is difficult to register multiple layers with high accuracy (< 1 μm over 1 mm) because of the elastomeric nature and the high coefficient of thermal expansion of the materials used for the stamps. These properties can result in deformation of the features in the stamp when placed in contact with a rigid substrate. The low contrast between the raised and recessed regions of the stamp also makes it difficult to register patterns optically. These difficulties in registering multiple layers of patterning using PDMS stamps have limited the use of soft lithography to those applications where one, or at most two, levels of patterning are necessary.

Multilevel stamping

In an effort to overcome this limitation, Tien *et al.* developed a technique for registering multiple steps of patterning using a single PDMS stamp that contains multilevel topology.[132] The details of the technique are described elsewhere.[132] Briefly, each level of the stamp was inked with different molecules. When the stamp was placed in contact with a rigid substrate, only

(Caption continued from previous page

poly(methylmethacrylate) patterned by this technique. (c) Optical micrograph of patterned bleaching of a thin film of phloxine B-doped poly(vinylphenol). (d) Optical micrograph of the output of light from a 1 × 4 optical splitter fabricated in the film described in (c). (e) Plot of the intensity versus position along the edge of the waveguides. The scheme and images in (a) and (c)–(e) are reproduced with permission from ref. 126 (Copyright 2004, American Institute of Physics) and the image in (b) from ref. 125 (Copyright 2001, American Association for the Advancement of Science).
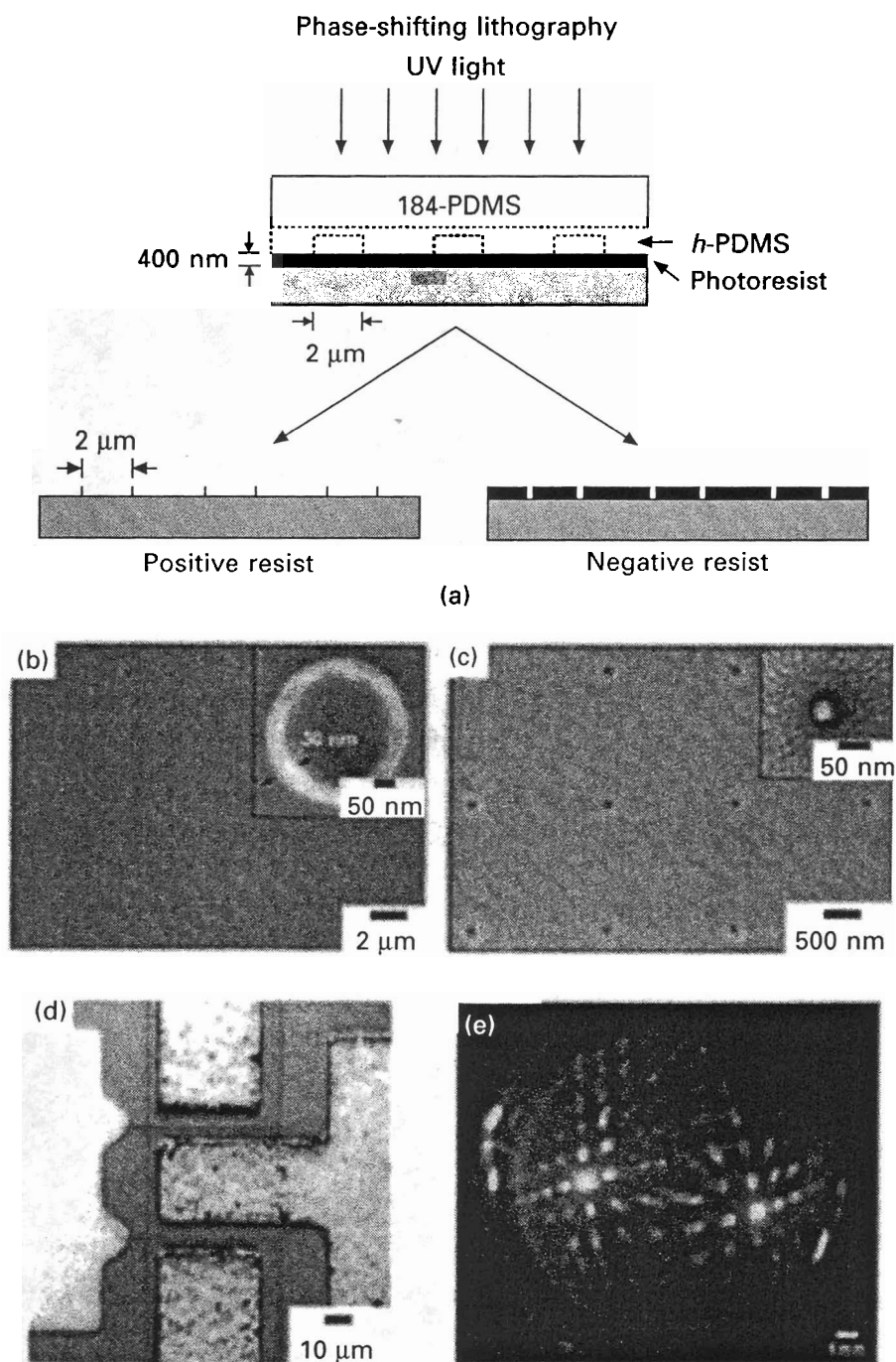
3.15 (a) Scheme for phase-shifting lithography using conformal phase masks. (b) and (c) Scanning electron micrographs of features in photoresist (rings (b) and holes (c) fabricated by this technique. (d) Scanning electron micrograph of a HEMT GaAs/AlGaAs-based transistor. The gates in this device were patterned using this technique. (f) Photograph of the diffraction of light from a spherical surface with surface features patterned by phase-shifting lithography using a conformal phase mask. This photograph shows an example of patterning sub-200-nm features on non-planar surfaces (1-cm-diameter steel spheres coated with photoresist) by soft lithography. The images in (b) and (c) are reproduced with permission from ref. 130 (Copyright 2002, American Chemical Society), the image in (d) from 131 (Copyright 2000, Elsevier B.V.), and the image in (e) from 132 (Copyright 2003, Wiley-VCH).

the tallest raised features were in conformal contact so patterning occurred only in these regions. Subsequent levels of the stamp were placed in contact with the substrate by applying pressure to the stamp. This technique was used to pattern a surface with regions of Au and Ag (Fig. 3.16(a)) and fluorescently labeled proteins (Fig. 3.16(b)) in register.
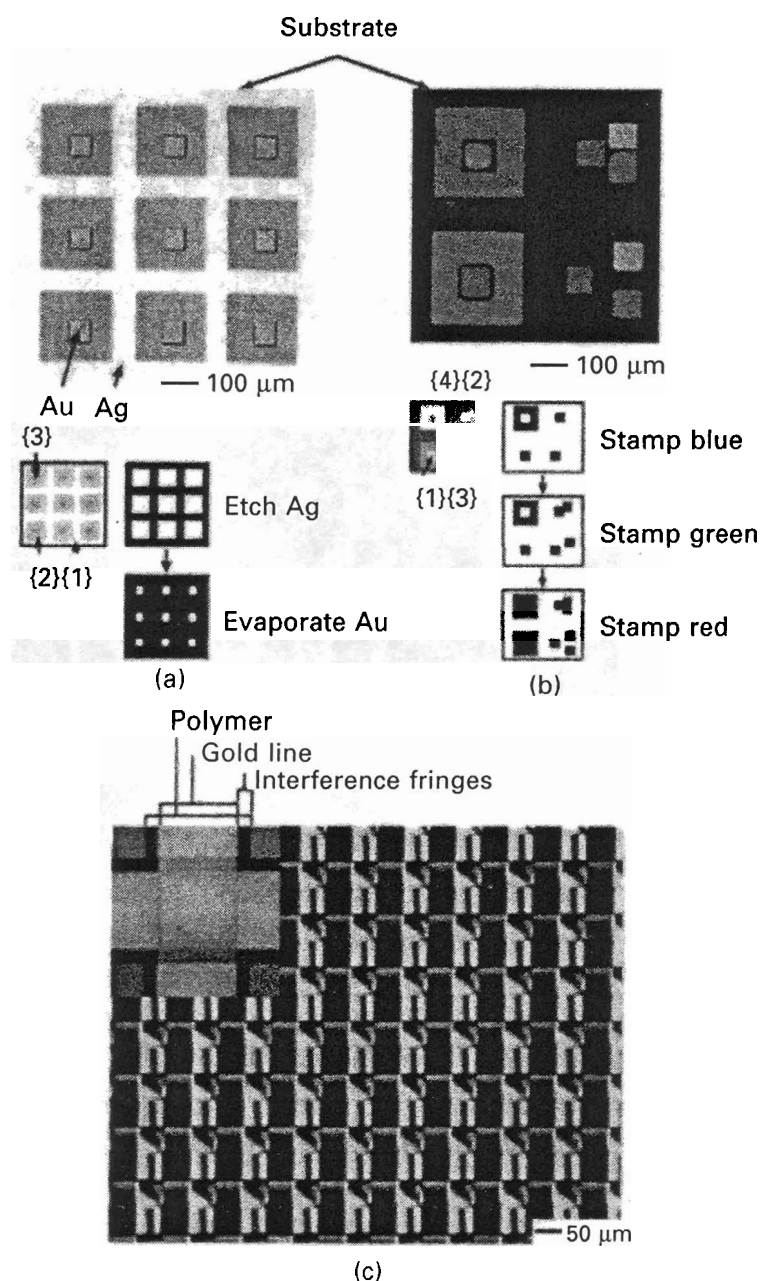
3.16 (a) and (b) Optical micrograph and scheme of fabrication for a patterned substrate generated by a combination of etching and evaporation using a three-level membrane. The numbers in the brackets represent the different levels of the multi-level stamp with the highest number as the most recessed feature. (c) Scanning electron micrographs of a crossed wire array fabricated by microcontact printing and patterned self-assembly. The images in (a) and (b) are reproduced with permission from ref. 133 (Copyright 2002, National Academy of Sciences, USA). The images in (c) are reproduced with permission from ref. 134 (Copyright 2000, Elsevier B.V.).

Patterned self-assembly of polymers

Crossed wires that are electrically isolated from one another are integral components of microelectronic devices. The standard techniques to prepare arrays of crossed wires include multiple steps of pattern transfer and registration. Black *et al.* used μCP and patterned self-assembly to pattern such a system without the need for complex steps of registration.[133] The details of the technique are discussed in the original mansuscript.[133] SAMs of carboxylic acid-terminated alkanethiolates patterned by μCP on Au made those regions hydrophilic. The unpatterned regions were rendered hydrophobic by washing the surface with a solution of methyl-terminated alkanethiolates. Hydrophilic, insulating polymers (e.g., polyurethanes, epoxies, or some photoresists) deposited by spin coating or dip coating stuck only to the regions patterned with the hydrophilic SAM. The regions of the gold not coated with polymer were removed by wet-chemical etching. This process was repeated to produce an array of electrically isolated, crossed wires (Fig. 3.16(c)) with only one step of registration necessary (i.e., a simple 90° rotation of the stamp with respect to the orientation of the first set of wires).

3.3   Conclusions and outlook

Soft lithography is not meant to replace the high-resolution tools (i.e., electron-beam and laser lithographies and photolithography) used to generate masters for micro- and nanofabrication of integrated circuits. The combination of the two sets of techniques enables routine and cost-effective microfabrication – and potentially of nanofabrication – of functional devices. Soft lithography has six advantages over conventional techniques (e.g., photolithography and electron-beam lithography).

1. It is well suited for fabricating low-cost, disposable devices, and tools for analysis, because the fixed costs are low.
2. It can generate prototype devices rapidly – the time from design to prototype can be less than 24 hours.
3. It can pattern features smaller than those by photolithography because it is not subject to the limits of optical diffraction.
4. It can pattern features on both planar and non-planar surfaces.
5. It can be integrated easily into existing manufacturing processes and facilities.
6. It may be possible to pattern large areas (> 1 m^2) in a single step; this limit is dictated by the size of the stamp rather than the size of the beam spot, uniformity of the intensity, and variations in focus. Initial efforts towards the patterning of these large areas have been successful (Fig. 3.17).[134]
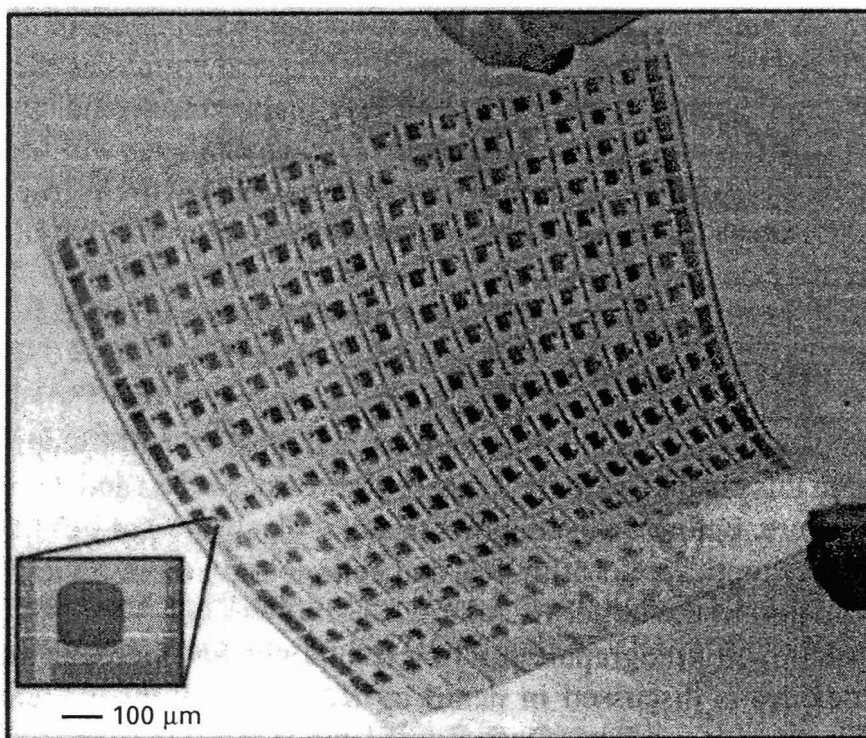
3.17 Photograph of a backplane for an active-matrix TFT display prepared using soft lithographic techniques. The inset is a photograph of an individual organic transistor. This image was reproduced from ref. 135 (Copyright 2001, National Academy of Sciences, USA).

There are three disadvantages of the use of soft lithography in the fabrication of functional microdevices. First, the optical (e.g., low contrast of the features) and physical (e.g., high coefficient of thermal expansion and low elastic modulus) properties of the elastomeric stamp make it difficult to register multiple lithographic steps with accuracy of < 1 µm. Secondly, the stamps are subject to distortion of the features because of their elastomeric nature and because of their high coefficient of thermal expansion; these properties of the stamp limit the use of soft lithographic techniques to applications where small distortions or defects do not affect device performance. It is therefore unlikely that soft lithography will replace photolithography as the technique used most commonly to fabricate complex microelectronic devices such as microprocessors. Thirdly, the PDMS-based stamps are not stable to many organic solvents[135] or at high (> 200 °C) temperatures.

A wide range of disciplines (e.g., biology, chemistry, engineering, and physics) have adopted soft lithography. The interdisciplinary use of soft-lithographic techniques has enabled the development of new capabilities in each of the aforementioned areas of science; examples include the patterning of cells on surfaces for cell-based assays[27] and the rapid turnaround of prototype and single-use devices in microfluidics[14] and biology.[6] The continued development of soft-lithographic techniques through interdisciplinary research

may enable methods of microfabrication for which the extension of conventional techniques is not straightforward, such as large-area, macroelectronic devices[134, 136, 137] and non-planar electronic and optical devices.[138–143] It is also unclear how conventional techniques will successfully pattern features having sizes < 50 nm over large areas rapidly and cost-effectively. The combination of soft lithography and patterned self-assembly may be a solution to this problem.

3.4   Further information

The examples of functional microdevices fabricated by soft lithography that are listed in this chapter are only a subset of those described and demonstrated in the literature. Below we list reviews that describe the use of soft lithography in electronics, optics, microfluidics, and cell biology; these reviews provide an introduction to the larger literature.

The use of soft lithographic printing techniques for microelectronics and optical devices is discussed in detail by Rogers in 'Rubber Stamping for Plastic Electronics and Fiber Optics'.[144] Gates et al. review soft lithographic techniques for nanofabrication in 'Unconventional Nanofabrication'.[145]

The use of soft lithography to fabricate microfluidic devices is discussed in detail by Whitesides and Stroock in 'Flexible Methods for Microfluidics'[12], Ng et al. in 'Components for Integrated Poly(dimethylsiloxane) Microfluidic Systems',[9] McDonald et al. in 'Fabrication of Microfluidic Systems in Poly(dimethylsiloxane)',[14] and Quake and Scherer in 'From Micro- to Nanofabrication with Soft Materials'.[146] The use of PDMS-based microfluidic channels in biology and biochemistry is described by Sia and Whitesides in 'Microfluidic Devices Fabricated in Poly(dimethylsiloxane) for Biological

Table 3.5 Examples of PDMS-based microfluidic components and devices

	Reference
Components	
Valves	146–153
Mixers	154–158
Functional Devices	
Dilutor	159
Immunoassay systems	160–165
DNA and protein separators	166–170
Cell sorters	171–174
Combinatorial screening devices	175–179
Tools for cell biology	180–183
Gradient generators	184–185
Bubble generators	186–190
Maze solver	191
Analog computer	192

Studies',[15] by Jiang and Whitesides in 'Engineering Microtools in Polymers to Study Cell Biology',[8] and by Whitesides *et al.* in 'Soft Lithography in Biology and Biochemistry'.[6] Table 3.5 is a list of examples of PDMS-based, microfluidic components and devices along with their respective references.[146–192] Microfluidic systems fabricated in PDMS and in other materials (e.g., glass and silicon) are discussed in further detail in Chapters 10 and 11.

Reviews of the use of soft lithography for applications in cell biology are described by Whitesides *et al.* in 'Soft Lithography in Biology and Biochemistry'[6] and by Jiang and Whitesides in 'Engineering Microtools in Polymers to Study Cell Biology.'[8]

3.5   Acknowledgements

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