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A Methacrylated Photoiniferter as a Chemical Basis for Microlithography: Micropatterning Based on Photografting Polymerization

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ABSTRACT: A polymer patterning technology based on photografting polymerization mediated by photoiniferter chemistry is presented as a simple microlithographic technique that affords flexibility in fabricating and subsequently modifying polymer substrates with various chemistries. In principle, the technique relies upon the design and synthesis of a methacrylated photoiniferter, (methacryloyl ethylenedioxycarbonyl) benzyl *N,N*-diethyldithiocarbamate (HEMA-E-In). This photoiniferter allows the production of micropatterned polymer substrates with surface or internally grafted chemical modifications. The ability to modify surfaces with covalently bound polymer is demonstrated where the thickness of the layer depends on the exposure time. Furthermore, patterning chemical surface modifications was achieved by combining this process with photomasks to produce micron-sized features (approximately 20 μm). The method is quite diverse and enables spatially controlled internal modification of polymer networks as demonstrated herein. The developed techniques should be very useful for the facile development of 2-D and 3-D patterned and surface-modified polymers for microfluidic and biomaterial applications.

Introduction

During the past decade, the development of micropatterned surfaces, especially biomaterial surfaces, has been extensively explored for applications ranging from biosensor technology[1−3] to tissue engineering[4,5] to fundamental studies of cell biology.[4−7] Specifically, biosensors based on living cells have been explored for environmental and chemical monitoring,[3] and positioning and patterning of the cells on these devices are critical to sensor performance. In tissue engineering applications, micropatterned surfaces have employed variations in charge, hydrophilicity and topology to regulate cell function and create organized structures. Endothelial cells spread and grow on large (>100 μm diameter) microcarrier beads,[8] whereas they rapidly die when bound to small (4.5 μm) extracellular-matrix-coated beads.[9] Chen et al. used micropatterned substrates to control the shape of human and bovine capillary endothelial cells.[7] They varied the extent of cell spreading while keeping the total cell−matrix contact area constant by culturing cells on substrates with 20, 5, and 3 μm diameter islands, separated by 40, 10, and 6 μm, respectively. They found that the extent of spreading (the projected surface area of the cell), and not the area of the adhesive contact, controlled cell life and death. Mrksich et al. used microcontact printing to pattern gold and silver substrates into regions of oligo-(ethylene glycol) groups and methyl groups.[10] After coating the substrates with fibronectin, bovine capillary endothelial cells attached only to the methyl-terminated, fibronectin-coated regions of the patterned, self-assembled monolayers. Scotchford et al. cultured primary human osteoblasts on carboxylic acid- and methyl-terminated self-assembled monolayers of alkylthiols on gold and measured kinetics of cell attachment and proliferation on these substrates.[11] After 24 h the number of cells attaching to carboxylic acid-terminated monolayers was 10 times greater than on methyl-terminated monolayers. The patterns of the carboxylic acid-functionalized areas also strongly influenced the morphology of the attached cells.

From a biomaterial perspective, techniques that enable facile production of topologically and chemically controlled regions on the size scale of a cell and greater are highly desirable, and a basis for many biomaterial patterning techniques is found in photolithography, a technique that was originally developed for the semiconductor industry. In the method, a silicon oxide substrate is coated with a thin layer of photoresist and irradiated with UV light through a mask. The exposed regions are removed in a developing bath to reveal complementary patterns of silicon dioxide and photoresist. Subsequent immersion of the substrate in a solution of alkyltrichlorosilane forms siloxane organic layers. The remaining photoresist is then removed, and a different siloxane is formed in the complementary regions. Photolithography readily achieves a spatial resolution of 0.13−0.15 μm, but the required photolithographic equipment and a controlled environment facility make this technique expensive.

Alternatively, microcontact printing, which uses an elastomeric stamp for pattern transfer, has been widely reported as a nonphotolithographic micropatterning technology. As an example, it can conveniently be used to pattern alkanethiolates on gold surfaces with features as small as 1 μm.[4,12] Spatial resolutions as small as 200 nm can be achieved in special cases.[13] The stamp used in microcontact printing is formed by casting poly-

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(dimethylsiloxane) (PDMS) against an appropriate relief structure, usually a photolithographically produced master. The PDMS pattern is then inked with a solution of alkanethiol in ethanol, dried, and manually brought into contact with a gold surface. Conformal contact between the elastomeric stamp and surface and the rapid reaction of alkanethiols with gold permit the surface to be patterned over an area several cm^2 in size with edge resolution of the features better than 50 nm. Because microcontact printing is a technique that does not require stringent control over the laboratory environment, it can produce micron-scale patterns conveniently and at a low cost relative to photolithographic methods. Microcontact printing has also been used to pattern alkylsiloxanes on the surfaces of SiO$_2$ and glass and on nonplanar and contoured surfaces.[13,14] However, both photolithography and microcontact printing technologies share some common disadvantages, such as lengthy preparatory procedures and low flexibility with regards to usable surface chemistries. Thus, new micropatterning technologies are needed, especially for the biomaterials community, that combine the desirable features of low cost and simplified operation with wide compatibility with a variety of polymer substrates.

To address these issues, photoiniferters have been used to modify the properties of polymeric surfaces[15,16] and developed as a method to prepare micropatterned surfaces.[17−22] Photoiniferters are classified as dithiocarbamate derivatives, which means, as first proposed by Otsu et al., that they act as an initiator, transfer agent, and terminator.[23,24] The UV photolysis of a dithiocarbamate molecule yields a reactive carbon radical and a less reactive or nonreactive dithiocarbamyl radical. The carbon radical is usually a benzyl radical, which can react with a vinyl monomer to initiate a radical polymerization. The dithiocarbamyl radical reacts weakly or not at all with a vinyl monomer but can terminate the polymerization by recombining with a growing polymer chain. When the photoiniferter is chemically bound to a surface, a polymer chain can be generated from the surface. Furthermore, when a photomask is used to restrict UV light incident on the substrate surface, a pattern of grafted polymer chains can be created.

By using a custom-designed apparatus operated by an X−Y step motor, Matsuda and co-workers prepared a surface upon which three to five different water-soluble polymer regions were photografted with micro-order precision on the same substrate.[17,22] Seeding and culture of endothelial cells on the micropatterned surface yielded markedly reduced adhesion on poly(*N,N*-dimethylacrylamide) and poly(2-hydroxylethyl methacrylate). Poly(*N*-[3-(dimethylamino)propyl]acrylate potassium salt) and poly(methacrylic acid sodium salt) regions promoted cell adhesion and growth, whereas enhanced adhesion was initially observed but then became markedly reduced over time on poly(3-sulfopropyl methacrylate potassium salt).

In Mastuda's studies, two methods were used to make the photoactive polymer substrates. In the first method, a photoactive monomer, typically a vinylbenzyl *N,N*-diethyldithiocarbamate, was copolymerized with styrene.[19] The photoactive polymer was then dissolved in toluene solution (2 wt %) and cast on one side of a PET film. A cross-linked polystyrene film was achieved by irradiation with a ^{60}Co γ-ray source. The substrate was then used in photopatterning with monomer/water

solutions. In the second method, Nakayama et al. made highly cross-linked polystyrene films with chloromethylate groups.[20] The film was subsequently modified by potassium *N,N*-diethyldithiocarbamate trihydrate to attach photoactive dithiocarbamate groups to the surface. Three different polymers were grafted onto the same substrate surface using this technique. Cross-linking of the films was necessary to allow the use of organic solvents in the sequential modification procedures.

Matsuda and co-worker's work showed that using a photoiniferter-mediated polymer substrate is a simple and direct way to make a patterned polymer surface. This technology is very different from the commercially used techniques of surface patterning. No photoresist or stamp is needed for patterning, and there appears to be more chemical flexibility with this technology than in present photolithography and microcontact printing techniques. For further clarification, the technique is a photolithographic grafting process based on polymer grafting chemistry. The polymer forms in the exposed area, directly from the liquid monomer, and transfers the photomask pattern. However, there are still some limitations in the photoiniferter patterning method currently presented in the literature. For example, the technique is not convenient for patterning non-water-soluble monomers. In addition, the commercial photolithographic or microcontact printing technology produces patterns on the surface of substrates, namely, surface patterning. Neither of these approaches has yet to report patterning of polymer substrate throughout its thickness (i.e., throughout the bulk of the material). Three-dimensional modification, or internal patterning, enables one to fabricate a polymer substrate with varied properties as a function of space.

A general methodology for making diethyldithiocarbamated polymer substrates is needed such that materials can be modified chemically in two or three dimensions, with a high degree of spatial control, to incorporate desirable properties for a diverse array of biomaterials applications. For example, thick polymer patterns have the potential to produce microchannels, which would be beneficial in microfluidic applications. Beyond surface modifications, micropatterned internal grafts in a polymer substrate would enable regional variations in the polymer properties in three dimensions. To test the feasibility of these concepts, a methacrylated carbamate molecule was synthesized as a functional photoiniferter molecule in the present work. This functionalized photoiniferter was then incorporated into various polymer substrates and the ability to generate 2-D and 3-D patterned substrates investigated.

Experimental Section

Materials. All monomers were dehibited using De-hibit 100 ion exchange resin before reaction. The following methacrylate monomers were used in making the polymer substrate: *n*-butyl methacrylate (BMA, Aldrich, Milwaukee, WI), *n*-hexyl methacrylate (HMA, Aldrich, Milwaukee, WI), 2,2,3,3-pentafluoropropyl methacrylate (PFMA, Aldrich, Milwaukee, WI), and 1,2-dodecyl dimethacrylate (DDMA, Aldrich, Milwaukee, WI). A UV photoiniferter, *p*-xylene bis(*N,N*-diethyldithiocarbamate) (XDT, 3M Corp., Minneapolis, MN),[23,24] was used as a co-initiator in photocured formulations (Table 1, F-I−F-II) of substrate preparation. The addition of XDT may reduce direct initiation from HEMA-E-In. Benzoyl peroxide (BPO, Aldrich, Milwaukee, WI) and *N,N*-dimethylaniline (DMA, Aldrich, Milwaukee, WI) were used as a bimolecular initiating system in thermally cured formulations (Table 1, F-II−F-IV)

Table 1. Substrate Formulation and Polymerization Conditions

| monomers (% molar ratio)	F-I	F-II	F-III	F-IV	F-V
BMA		67.0			29.0
HMA	32.1		32.0	88.9	
DDMA	35.5	30.0	35.0	1.0	
PFMA	2.7	1.0	3.0	1.5	
HEMA-E-In	29.7	2.0	30.0	8.6	13.0
CN965					58.0
XDT[a]	1.4	0.5			0.7
BPO[a]			0.5	0.45	
MDA[a]			0.5	0.45	
polymerization conditions	photocure, 1 h	photocure, 1 h	50 °C/10 h	50 °C/10 h	photocure, 1 h

[a] Weight fraction by total monomer weight.

of substrate preparation. A polyester urethane diacrylate (CN965, supplied by Sartomer Co., molecular weight = 3000) was also used to prepare a polymer substrate (Table 1, F-V) for internal grafting. The following monomers were used to make micropatterned polymer layers on the surfaces of polymer substrates: 2-hydroxyethyl methacrylate (HEMA, Sigma, St. Louis, MO), poly(ethylene glycol) (400) monomethyl ether monomethacrylate (mPEG400 MA, Polysciences, Warrington, PA), and triethylene glycol dimethacrylate (TEGMA, Aldrich, Milwaukee, WI). HEMA was also used in internal patterning.

Synthesis of (Methacryloyl ethylene-dioxycarbonyl) Benzyl *N*,*N*-Diethyldithiocarbamate (HEMA-E-In): the Functionalized Monomer Iniferter. Briefly, 4-(chloromethyl)benzoyl chloride (2.6×10^{-2} mol, 5 g), HEMA (3.9×10^{-2} mol, 5.1 g), triethylamine catalyst (3 g), and 50 mL of ethyl acetate (all from Aldrich, Milwaukee, WI) were added to a 250 mL round-bottom flask with a magnetic stir bar. The flask was purged with dry N_2 gas, sealed, placed in a salt—ice bath (<0 °C), and allowed to react overnight. The resulting white powder precipitate was filtered and washed with deionized water. Then, sodium diethyldithiocarbamate trihydrate (3.9×10^{-2} mol, 9 g) was added, and the reaction was carried out for 5 h with continuous stirring at 60 °C. FTIR and ^{1}H NMR were used to confirm the structure of the product. Further details of the synthesis are available elsewhere.[25]

Preparation of *N*,*N*-Diethyldithiocarbamated Polymer Substrates. The substrates used for patterning are based on formulations (shown in Table 1) with varying monomer composition and functionalized monomer—iniferter content. Monomer solutions were cast into a glass mold and polymerized either thermally at 50 °C for 10 h or photochemically for 1 h with 365 nm UV light at ~10 mW/cm² (BlakRay), depending on the formulations. Because the substrate contains the monomer—iniferter, the substrate can be used to pattern polymer layers on the surface under simple masking and irradiation conditions. In addition, all of the substrates contain a high concentration of dimethacrylate cross-linker. Highly cross-linked architectures prevent the substrates from swelling when placed in contact with various monomer solutions during grafting.

Preparation of Micropatterned Polymers. Schematic diagrams of the devices and procedures used for micropatterning are shown in Figure 1. For surface patterning, substrate formulations of F-I to F-III were used. Upon polymerization, a piece of polymer substrate was placed on a support glass slide, and glass spacers with thicknesses of 100—200 μm were used to control the spacing between the photomask and the substrate as well as spread the grafting monomer uniformly over the substrate. A commercially available light source (Novacure, EFOS) equipped with a liquid light guide and a 365 nm band-pass filter were used to initiate surface and internal grafting polymerization. A photomask with a slit width of 180 μm and interslit distance of 42 μm was used to create the surface patterns. The monomer layer and polymer substrate were irradiated for 1—40 min by UV light transmitted through a collimating lens and the photomask. A light intensity of 70 mW/cm² (with the 365 nm filter) was measured at the substrate surface. During photopolymerization, the temperature of the polymerized samples was maintained at
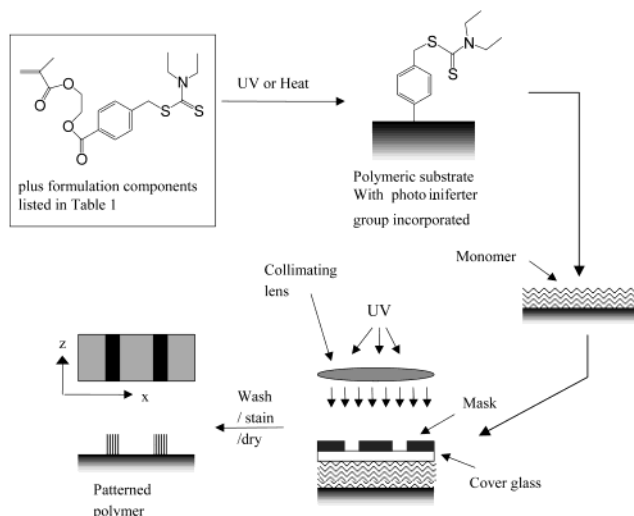
Figure 1. Schematic diagram of the microlithography surface modification principle and method.

ambient conditions. Afterward, the irradiated sample was thoroughly rinsed with distilled water and acetone to remove unreacted monomer and homopolymers and subsequently dried in air.

For internal patterning, substrate formulation F-IV was used. To create the internal grafts, the substrate was swollen in a HEMA solution that contained 0.2 wt % of a methacrylated dye (Red-MA, the dye was used so that we could easily visualize internal micropatterned grafts) for at least 2 days (until the substrate was uniformly red in color). The swollen substrate was then contacted with a photomask directly and exposed to patterned UV light for 10—15 min (Figure 1). The exposed substrate was then swollen in chloroform and ethyl acetate for 48 h at ambient condition to extract unreacted monomer and soluble, unattached polymer chains. The washing step was processed until no significant double bond peak (6165 cm^{-1}) was observed in near-IR spectra. This methodology has been described previously.[25,27] The remaining, incorporated Red-MA-HEMA copolymer grafts were readily visualized using light microscopy by distinct, spatially varying color patterns compared to the unmodified, colorless substrate regions. To synthesize the Red-MA, Dispersed Red 1 (Aldrich, Milwaukee, WI) was methacrylated by reacting the dye with methacrylol chloride in chloroform/triethylamine solution. After purification, ^{1}H NMR was used to verify the methacrylated structure.

Preparation of Surface-Anchored, Micropatterned Hydrogels. The hydrogel was synthesized from a monomer formulation of 5 wt % sodium methacrylic acid (Aldrich, Milwaukee, WI), 80 wt % methoxylpoly(ethylene glycol) 200 methacrylate (PEG200MA) (Aldrich, Milwaukee, WI), and 15 wt % deionized water. Chain transfer leads to the formation of a cross-linked network. A highly cross-linked polymer substrate was placed on a support glass slide. The monomer to be grafted was placed on the substrate along with glass spacers (300 μm thick) to control the spacing between the photomask and the substrate as well as spread the monomer

uniformly over the substrate (F-I in Table 1). A commercially available light source (Novacure, EFOS), equipped with a liquid guide and a 365 nm filter passed through a collimating lens, was used to initiate grafting. To create the surface-patterned gel, a photomask of square grids (62 μm bars separated by 438 μm) was used. The top monomer solution and polymer substrate were irradiated for 10 min with 70 mW/cm^2 of UV light as measured at the substrate surface. After irradiation, the sample was thoroughly rinsed with distilled water and acetone to remove unreacted monomer and soluble polymer and then dried in air.

Instruments and Surface Characterization. Infrared spectra and near-infrared spectra were recorded with a Nicolet Magna-IR 750 II spectrometer at 4 cm^{-1} resolution. ^{1}H NMR spectra of the functionalized monomer−iniferter were collected on a Varian VXR300S Unity spectrometer. Samples were dissolved in CDCl$_3$ containing 1% TMS as an internal reference.

The chemical structure of the outermost substrate surface layer was characterized by FT infrared spectroscopy (a Nicolet Magna-IR 750 II) at 4 cm^{-1} resolutions. The surface topography of each micropatterned substrate and its thickness were characterized using light microscopy with a Nikon Optic system (S & M Microscopes, Inc.). The spatial dimensions of the grafted layers were standardized by known dimensions of the photomask. Dyes were used to enhance the contrast between chemically modified regions. The grafted hydrophilic polymer regions were stained with an aqueous basic blue (Aldrich, Milwaukee, WI) solution, which stains the hydrophilic polymer regions blue, independent of pH. In addition, an aqueous Rose Bengal (Aldrich, Milwaukee, WI) solution was also used to stain the hydrophilic polymer regions, which stains the polymer red at pH < 7. Controls demonstrated that the dye did not stain the hydrophobic polymer substrates used in these studies (results not shown).

Results and Discussion

Substrate Characterization. As presented in Figure 1, the micropatterning technique proposed here utilizes UV light to initiate polymerization at specific regions of the polymer substrate. The radicals formed in these regions initiate polymerization of the monomer's vinyl groups in solution to covalently graft thin layers of polymer to the substrate. After removing unpolymerized monomer and soluble homopolymer, the surface-anchored polymer layer or internal grafted polymer remains as the new micropatterned region.

The purpose of the newly synthesized monomer−iniferter (HEMA-E-In) is to introduce photoiniferter groups along the internal chains of a cross-linked polymer substrate, so that the dithiocarbamate group can be employed to initiate further photografting. The methacrylic double bond in HEMA-E-In allows copolymerization with other components in the substrate formulation (Table 1), so that the dithiocarbamate group is covalently incorporated throughout the polymer, including the surface of the polymer substrate. Polymer substrates can be prepared without using additional initiators, like XDT or BPO. It was demonstrated in previous work that surface grafting could be achieved using substrates prepared solely by photoinitiation of HEMA-E-In.[25,27] The purpose of using XDT or thermal initiators to polymerize the initial polymer substrate is to maintain the unreacted form of the dithiocarbamate group on the poly(HEMA-E-In). This may not be important for surface patterning; however, it is very important for internal patterning because grafting is conducted from internal chains of a cross-linked polymer substrate.

ATR−FTIR spectroscopy was used to verify the chemical composition of the polymer surfaces and to
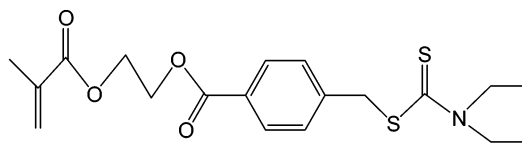
confirm the presence of reactive dithiocarbamate groups. The dithiocarbamate unit and benzene ring are unique to the monomer−iniferter molecule in the substrate formulations. Characteristic peaks from both of these groups are observed in the ATR−FITR spectra of the polymer substrates (Figure 2). Figure 2 also shows that almost complete conversion of the double bonds is obtained in both the photochemically or thermally cured substrates. In addition, quantitative ATR−FTIR results reveal that the higher the concentration of monomer−iniferter used in the substrate formulation (e.g., F-I vs F-II), the higher the concentration of dithiocarbamate groups (1485, 1267 cm^{-1}) in the substrate. This higher concentration correlates to a higher concentration of initiator sites for surface-mediated polymerization.

Surface Patterning. Figure 3 demonstrates that micropatterns are readily transferred from a photomask to polymer substrates with a variety of preparation methods and iniferter concentrations. Figure 3a shows the geometric features of the photomask used in surface patterning. If the patterned stripes of grafted polymer (stained areas in Figure 3b−d) are compared to those of the photomask, it is readily observed that their dimensions are preserved with high fidelity. Figure 3b,c demonstrates that, independent of the substrate preparation method, micropatterns can be transferred by UV irradiation and surface grafting. Also, because the F-II substrate contains less photoiniferter groups, it took a longer exposure time to achieve realistic patterning.[25,27]

To enhance our understanding of the unique effects of the photoiniferter chemistry, a photoinitiator (not a photoiniferter), DMPA, replaced the photoiniferter in certain substrate formulations. In these substrates (polymerized without the iniferter) no patterning or grafting was observed. These results illustrate that the photoiniferter chemistry is capable of making covalently bound polymer layers.

Internal Patterning. As indicated by the ATR−FTIR spectra and surface patterning results, the dithiocarbamate group of the monomer−iniferter is chemically bound to the surface of the polymeric substrate during copolymerization. Actually, the dithiocarbamate group is not only attached to the surface of the substrate but is also present throughout its entire structure since the methacrylate group in the HEMA-E-In molecule is polymerized homogeneously throughout the cross-linked polymeric network of the substrate. To support this claim, a loosely cross-linked substrate network (F−V) was cured and swollen in a HEMA solution with 0.2 wt % Red-MA as a polymerizable dye. After the system reached equilibrium in its swollen state, a patterning experiment was performed with an irradiation time of ~10−15 min. After removing the unreacted monomer and homopolymers, the internal patterning appears, indicating covalently grafted dye throughout the polymer network.

Figure 4 presents the results for internal patterning. The side view (Figure 4b) clearly shows that the grafts grow throughout the substrate; however, the dye partially absorbs the UV light. Since the substrate is about 2 mm thick, the grafting did not occur throughout the
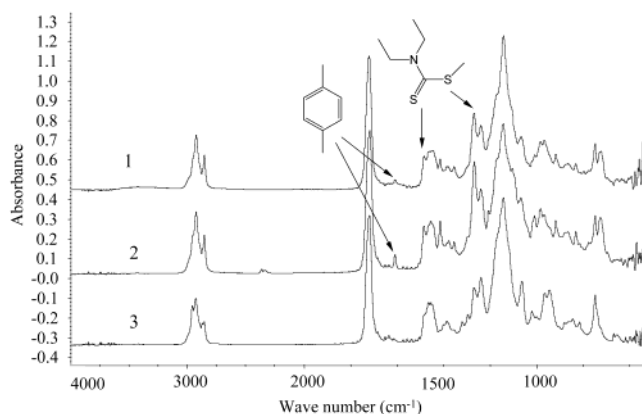
Figure 2. Comparison of the ATR−FTIR spectra of the substrates containing various photoiniferter concentrations. Curve 1: F-IV, thermally polymerized; curve 2: F-I, photocured; curve 3: F-II, photocured.
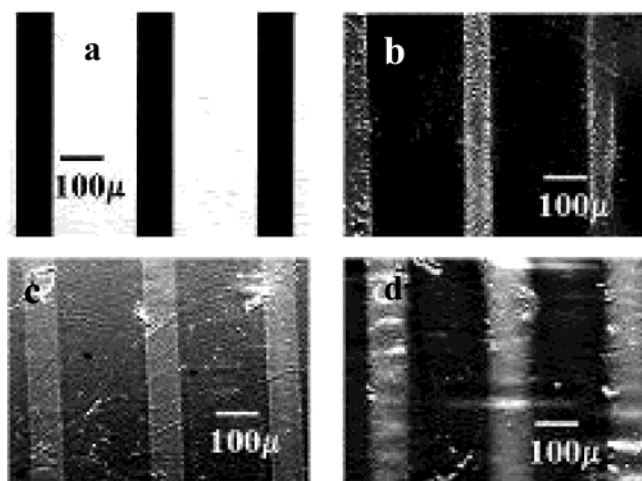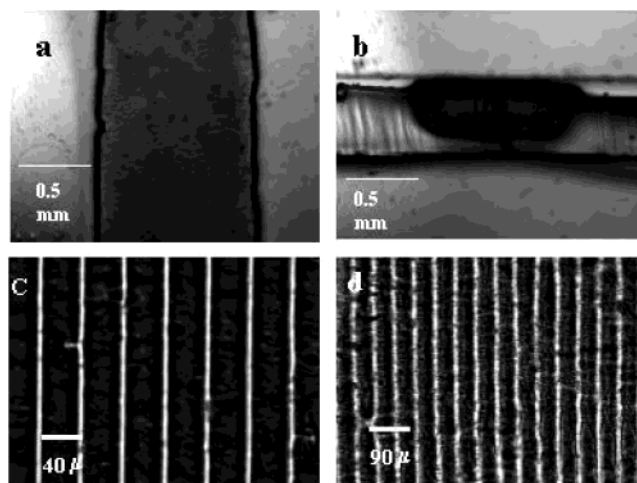

Figure 3. Comparison of surface micropatterning with varying concentrations of photoiniferter in the substrates. HEMA was grafted onto the substrate surface. (a) Mask, (b) F-I, 10 min irradiation; (c) F-II, 40 min irradiation; (d) F-III, 3 min irradiation.
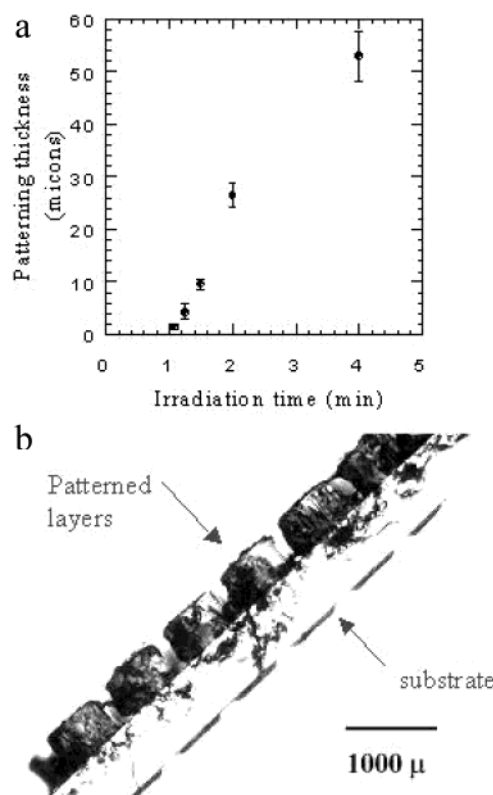

Figure 4. Internal grafting and patterning with various resolution. Substrate formulation is F-V. (a) Top view of an internal pattern, mask width 1 mm, 15 min irradiation. (b) Side view, same sample as (a). (c) Top view of an internal pattern, mask width 20 μm. (d) Same sample with (c) at lower magnification.

Figure 5. Capability for thickness control for the surface patterned polymer. (a) Thickness as a function of irradiation time, PEG400 MA as graft monomer F-II substrate formulation. (b) Side view of a thick patterned polymer layer, TEGMA as patterned monomer, F-II substrate formulation.

entirety of the substrate with the limited exposure time. Parts a and b of Figure 4 are patterns developed with a mask of 5000 μm bars. To achieve higher resolution, a mask with a 20 μm bar width and 20 μm pitch width was used. Figure 4c,d shows that high-resolution patterning was achieved successfully, but there is also some graft spreading. Factors affecting the fidelity of this 3-D process include the thickness of the substrate, exposure time, and collimation of the light source. The precision of 3-D pattern transfer is a focus of current, ongoing work.

This observation suggested that the hydrophilic HEMA monomer grafted not only on the surface of the substrate but also internally when the monomer is allowed to penetrate the reactive substrate. It is believed that novel materials can be produced by the internal-grafting method, and these materials would exhibit unique properties such as regional swelling and absorption.

Thickness Control of the Micropatterned Polymer Layer. In biomedical applications, topographic modulation of tissue response is believed to be one of the most important considerations in the design and manufacture of a biomaterial.[5] Various studies have indicated that it may be possible to design the surface texture of implanted materials to improve the perfor-

mance of an implant. With such enhancements in mind, Figure 5 illustrates that the present technology has the capability to control the thickness of the patterned polymer layer. Figure 5a shows that the average thickness of a patterned polymer layer, grafted by poly-(ethylene glycol) MA, increases almost linearly with irradiation time. After 4 min of UV irradiation, the thickness was approximately 52 $\pm$ μm. Such a thickness correlates to a molecular weight of graft polymer around $\sim 5.0 \times 10^7$ if the polymer remains linear and is not
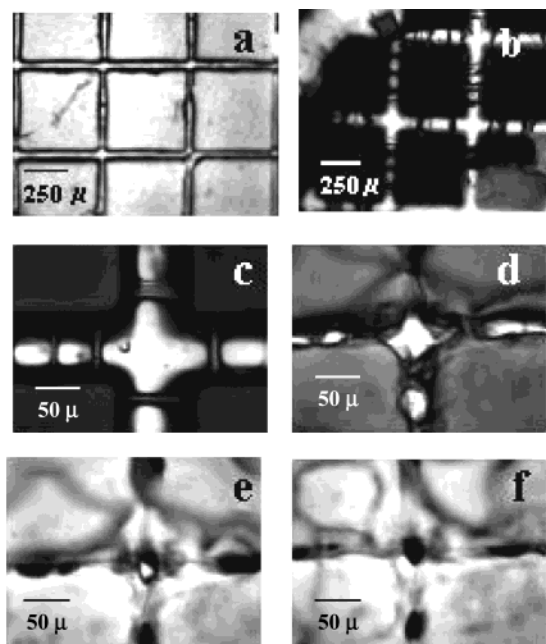
Figure 6. Microchannel formation on micropatterned, surface anchored hydrogels (~300 μm thick). Substrate formulation is F-I. (a) Swollen in deionized water for 2 h. (b) Swollen in pH = 2 solution and then dried. (c) Swollen in pH 2.0 buffer solution and then immerged into pH 10.0 buffer solution at (d) 4 min, 5 s; (e) 5 min, 57 s; and (f) 8 min, 9 s.

cross-linked. However, chain transfer is readily occurring during the surface-initiated polymerizations of these monomers.[26,27] Cross-linking occurs due to chain transfer reactions involving the poly(ethylene glycol) units in the monomer and leads to gelation effects and deviations from a purely surface grafting approach. While this leads to a higher polydispersity and deviation from a pure grafting mechanism, this behavior can also provide certain advantages as well, in terms of a simple approach to modify the substrate surface properties.

The capability to construct well-defined yet relatively thick patterned polymer layers may result in a progression from surface patterning to microfabrication for microfluidic applications.[28] As shown in Figure 5b, a three-dimensional structure is obtained when TEGD-MA, a divinyl monomer, is irradiated for 10 min in contact with a HEMA-E-In substrate. The thickness of the patterned polymer layer on top of the substrate in Figure 5b is approximately 140 ± 20 μm. One very important result in the experiment is that a well-defined pattern is still maintained with this relatively thick patterned layer. This result, along with the ability to accurately tune layer thickness by controlling irradiation time, makes this technology very attractive for a number of applications. One important and extremely useful application of this technique would be for constructing a variety of microfluidic devices for genomic applications, RNA and DNA analysis, and high-through-put pharmaceutical drug screening.

Patterning pH-Sensitive Microchannels. As a final demonstration, a pH-sensitive, surface-anchored hydrogel was patterned on a photoiniferter-confined polymer substrate (F-I) to create dynamic channels (Figure 6). Specifically, a surface attached gel was fabricated from a monomer solution of sodium methacrylic acid, poly(ethylene glycol) methacrylate, and a dimethacrylate cross-linker. Upon exposure through a photomask, a surface-anchored hydrogel was created

with a uniform thickness of ~300 μm and a ~500 μm spacing between the micropatterned parts, creating microchannels on the substrate surface. By introducing aqueous fluids of various pH on the device, the pH response of the hydrogel was investigated by observing dimensional changes in the micropatterned gel. Specifically, the ability to open and close the patterned microchannels was demonstrated as a function of time and pH to illustrate the potential for these approaches in fabricating microfluidic devices with controllable flow loops. Since the gel is covalently bound to the substrate, the device is robust and the behavior easily reversed for multiple uses. Figure 6 shows that the microchannels were completely closed in approximately 8 min once submerged in pH = 10 buffer solution. In the reverse process, the microchannels opened within 5−8 min in a pH = 2 buffer solution.

Conclusions

A method to surface and internally modify polymer substrates was developed by copolymerizing a methacrylated photoiniferter with various methacrylated monomers. This contribution illustrates the ability of surface-anchored photoiniferter molecules to initiate a grafting polymerization on a wide variety of polymer substrates. The pattern transfer time is controlled by the concentration of photoiniferter in the substrate, and the grafted polymer layer thickness is controlled by the exposure time. Grafted polymer layers, ranging in thickness from a few microns to over a hundred microns, are demonstrated. Surface patterns with dimensions on the order of 20−40 μm are easily achieved with inexpensive and fairly versatile processing techniques. Furthermore, results show that micropatterning can be accomplished wherever photoiniferter is present, whether on the substrate surface or within the substrate network. Internal micropatterning is a unique aspect of this method, and hydrophilic internal grafts were patterned into a hydrophobic substrate. This simple, one-step procedure allows 3D modifications to polymer substrates to construct regionally modified polymer with different degrees of hydrophobicity or other properties, such as electric charge.

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